Nakládal *et al. Geothermal Energy* (2024) 12:37
https://doi.org/10.1186/s40517-024-00313-6

Geothermal Energy

RESEARCH

Open Access

Methods of grout quality measurement in borehole exchangers for heat pumps and their rehabilitation

Petr Nakládal[1*], Martin Procházka[2], Viktor Goliáš[1] and Jaromíra Hrdá[3]

*Correspondence:
petr-nakladal@email.cz

[1] Faculty of Science, Charles University, Albertov 6, 120 00 Prague 2, Czech Republic
[2] Geotechnika a.S., Barrandova 988/4, 152 00 Prague 5, Czech Republic
[3] Institute of Physics of the Czech Academy of Sciences, Na Slovance 2, Prague 8, Czech Republic

Abstract

Methods and instrumentation for measuring grout quality in heat pump boreholes, including the measurement of groundwater flow through boreholes outside partly grouted borehole exchanger pipes, have been developed in the Czech Republic. A Semtex charge has also been developed to repair rock massifs, which reliably disconnects borehole exchanger pipes without severely harming the surrounding rock environment or buildings. The resulting hole can then be used for regrouting, thus preventing undesirable vertical water flow through the borehole.

Keywords: Geothermal energy, Heat pump, Carottage, Borehole repair

Introduction

The initial experiments with geothermal heat date back to 1904, when the first geothermal power plant was commissioned in the Larderello region of Italy (Di Raimondo 1955). Owing to technological advances, geothermal energy has become a popular heat source for ordinary households and small businesses since the beginning of the millennium. Owing to the principle of heat pumps, geothermal systems save ~ 2/3 of the energy (for 1/3 of the energy supplied, 2/3 of the geothermal energy is obtained), thereby contributing to lower energy consumption in heating buildings. However, the overall efficiency of these systems is low due to the physical nature of ground heat extraction (Zarrouk and Moon 2014). For large energy units, significant savings are also achieved not only in heat but also in electricity production (CHP units). Geothermal energy can be used by water-to-water heat exchanger systems, in which heat is extracted from groundwater or directly from the rock environment (ground-to-water) using ground heat exchangers (DiPippo 2012). Due to the physical nature of ground heat flow, surface ground heat exchangers built at shallow depths below the ground (Congedo et al. 2012) or exchangers created by one or a system of boreholes at depths of the first hundreds of meters (so-called dry heat recovery) are used. This research paper exclusively addresses the vertical ground heat exchangers formed by a borehole and its equipment (Ingersoll and Plass 1948; Ericsson 1985). Most of the scientific work in this field has focused on designing and modeling the physical phenomena of earth exchangers (Claesson and Hellström 2000; Shonder and Beck 1999). These scientific works mainly involve heat transfer between the rock and the heat pump medium and the optimal structure of the system (Muraya and O'Neal 1996; Sarbu and Sebarchievici 2014)

The vertical heat pump exchanger consists of a borehole to an appropriate depth, reinforcement with at least two pipes (U tubes), and grouting. An ideal ground heat exchanger created by one or a system of boreholes should be indifferent to the original hydrogeological parameters of the rock environment. Due to the hydrogeological structure of real rock masses, boreholes must pass through several hydrogeological aquifers in flow-through environments and fracture environments. To avoid the interconnection of different hydrogeological aquifers, the system of earth exchanger pipes installed in the borehole should be well grouted (Fig. 1). With the widespread use of dry heat, many industries and government officials in the country have warned of the dangers of interconnecting aquifers with inadequately grouted ground exchangers. It is clear that the lack of water in the landscape may be due to poorly constructed and inadequately injected heat exchangers for ground heat pumps instead of climate change.

For example, in the Federal Republic of Germany, a system of standards for the use of geothermal energy was already approved in 2001 (VDI 4640 2024a, VDI 2024b). When drilling in areas with problematic geology, the system of standards recommends that boreholes be grouted with ferromagnetic grout (Corson et al. 2021). The continuity of the grout in the borehole is then checked via magnetometry. If water flows through the ungrouted part of the borehole, the standard requires it to be

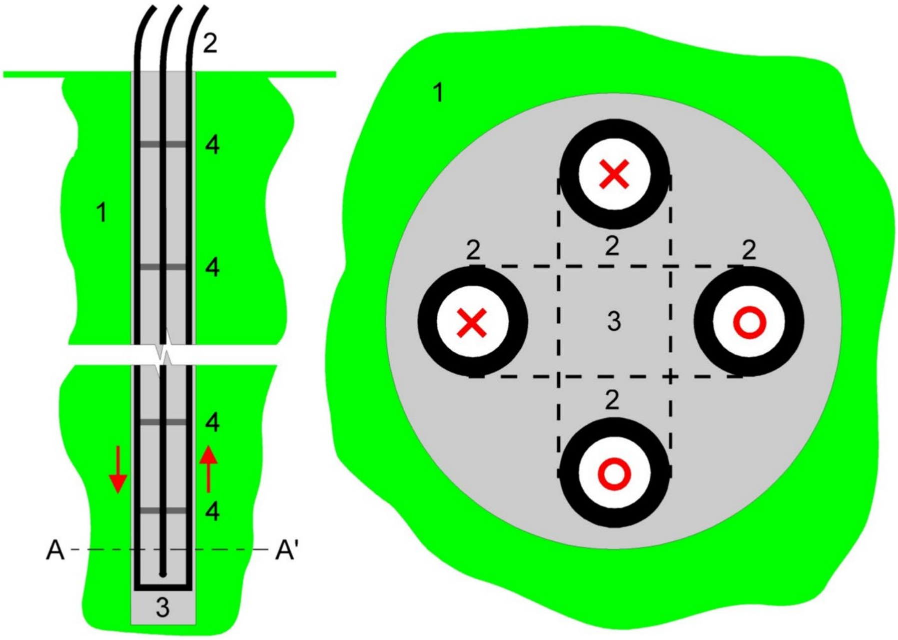


Fig. 1 Vertical section of the ground heat exchanger on the left, enlarged section A–A′ on the right. 1—rock mass; 2—U tubes of the heat exchanger; 3—grouting material; 4—centralizers between the tubes, red arrow—movement of the medium in the tubes

verified by thermometry [(VDI 4640 2024a, 2024b), part 5; chapter 8.3; July 2020)]. The ground heat exchanger is permitted to operate only when the grouting quality is proven by the methods described above.

If the Earth's crust is disturbed by a borehole located at a location with more than one hydrogeological aquifer at different piezometric levels, groundwater starts to flow through the open space (Fig. 2). This process creates a hydraulic short circuit between two aquifers. The rock environment is robust and indifferent to temporary hydraulic short circuits caused by drilling operations. Therefore, drilling operations will only affect groundwater levels in the immediate vicinity of the borehole up to a distance of ~ 100 m. A quick and high-quality grouting of the borehole with a heat exchanger will eliminate the created hydraulic short circuit. The aim of this study was to find suitable methods for detecting hydraulic short circuits caused by poorly grouted ground heat pump exchangers and to design and verify the function of remedial interventions to restore the natural state.

Research on the detection of grout continuity in ground heat pump exchangers started in 2015. The anticipated problems with hydraulic short circuits in multicollector rock systems prompted this approach. At that time, there was minimal experience worldwide with both the detection of continuity of grout in earth exchangers and its repair. Initially, the research was based on known carottage methods (well logging). For the study, the carottage probes were miniaturized to the diameters of the earth exchanger pipes. Parallel to the development of detection methods, new technologies were also validated, first for disposing of defective earth exchangers and then for repairing malfunctioning grouting. Initially, already lined ground exchanger boreholes had to be redrilled and

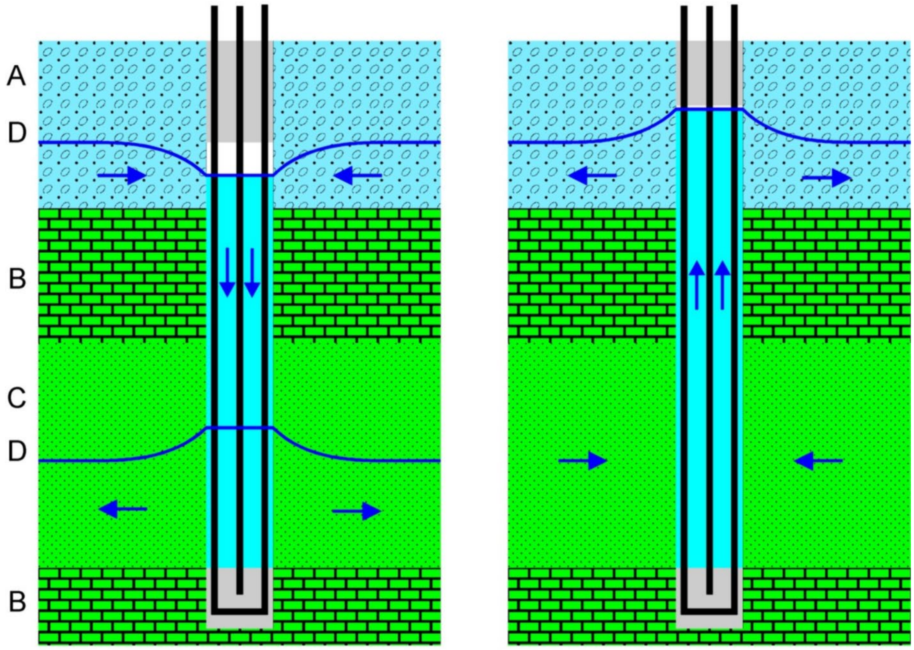
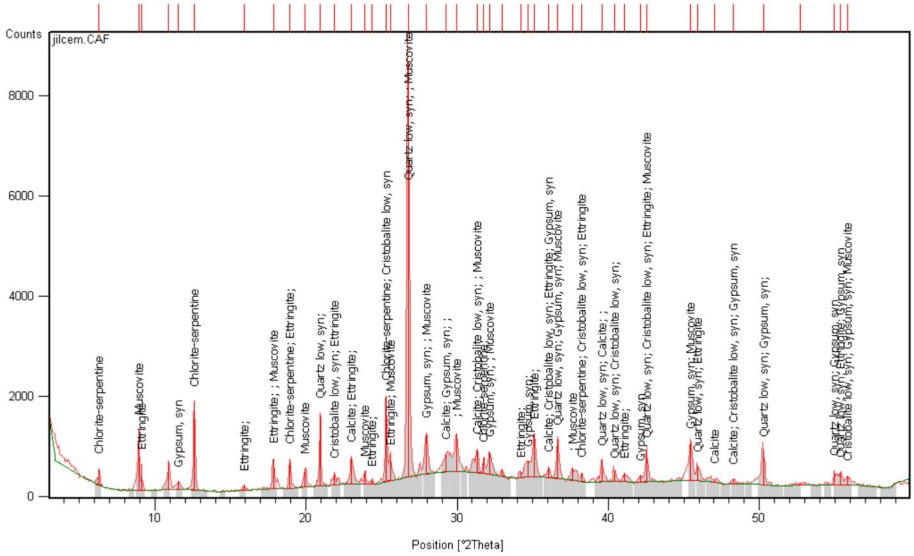


Fig. 2 Hydraulic short circuits in ground heat pump exchangers (left overflow to the lower collector, right overflow from the pressurized collector to the quaternary). A: Rock mass (gravels); B:Rocks of the hydraulic isolator; C: Aquifer (sandstones); D: Groundwater level, blue arrow—groundwater flow

were either disposed of or relined. The present research developed a measurement system independent of the ferromagnetic properties of grouting materials and a method for repairing failed ground exchanger grout. Sub-stages of the research have been presented at regional conferences. Further research focused on repairing earth exchangers with different levels of water flow in the borehole (loss and overflow).

Causes of hydraulic short circuits and their manifestations

The most common reason for poorly designed ground exchangers is technologically practical. Grouting materials are relatively expensive. Therefore, drilling companies compromise on their quality. A common misconduct is the dilution of grouts to lower densities than recommended by the manufacturer (https://www.fischer-spezialbaustoffe.de/). An extreme case is the fraudulent practice of drilling companies, which, upon detection of grout loss, pour dry grout into the borehole (it gets trapped on wet walls) to mask the effect of caverns. The problem also lies in the quality of the grouts. Currently, commercially manufactured grouts based on clay or cement mixed with microfillers (quartz, mica, clays; see Fig. 3) can be used in sediments with porosities up to the level of gravel sands or in tectonically intact rock masses (crystalline and sedimentary rocks). Experience to date has shown that currently commercially manufactured grouts fail in tectonically disturbed rocks. If a borehole encounters several fractured aquifers with different groundwater levels (see Fig. 2), the injection material with a dust grain size is washed into these aquifers. Due to the design of the heat exchanger (Fig. 1, Ingersoll and Plass



Pattern List:

Ref. Code	Compound Name	Score	Total Lines	Scale Factor	SemiQuant [%]
01-083-2466	Quartz low, syn	45	12	0.977	41
01-086-2340	Calcite	29	10	0.044	2
00-052-1044	Chlorite-serpentine	26	8	0.082	5
01-077-1317	Cristobalite low, syn	21	22	0.036	1
00-013-0350	Ettringite	14	39	0.049	3
00-033-0311	Gypsum, syn	8	38	0.033	2
00-014-0035	Calcium Silicate Hydrate	16	39	0.112	15
00-012-0739	Calcium Hydrogen Silicate	14	12	0.027	4
00-002-0058	Muscovite	28	19	0.146	28

Fig. 3 Results of the X-ray powder diffraction analysis of the hardened, commercially produced grouting mixture

1948), the loss of grouting may not be visi`ble on the surface. Boreholes for ground-source heat pump exchangers are not cheap, so the owners of such an affected borehole prefer to hire a good lawyer to convince local communities that the loss of water in the village was caused by drought. Another major reason for refusing to repair improperly engineered groundwater exchanger boreholes is their frequent installation under building foundations (Kayaci et al. 2019). The classical repair of such an installed exchanger, namely, its redrilling, would mean demolishing an already constructed building.

The major problem lies in the evidence that the constructed groundwater exchanger has caused groundwater levels to drop in its vicinity. Digging and disposing of a well are not an inexpensive affair, so the owner or the contractor wants solid proof that they are the ones who caused the water shortage in the village. The courts have accepted evidence consisting of the measurement of boreholes by a number of carottage methods (Mareš et al. 1979). The conventional apparatus for carottage measurements in boreholes has a diameter of ~ 40–50 mm (https://www.alt.lu/downhole-probes). Unfortunately, the most commonly drilled ground heat pump exchangers are made of PE pipes with an inner diameter of 20 mm or up to 33 mm. The problem of proving hydraulic shorts in ground heat pump exchangers must therefore be overcome by suitable methods using carottage probes with a diameter of up to 15 mm.

Methodology for measuring the quality of grouting and disposal of earth exchangers

Gamma–gamma-ray logging (GGL)

If the grouting mixture is flushed into the rock environment, then due to the nature of the earth exchanger design, air or water must be present around the PE pipe at this location. This change significantly affects the measured density. In 2015, initial tests involving rock density measurements with a small-diameter probe using Compton gamma-ray scattering were started at the Faculty of Science (Reynolds 1967). The components of the measuring equipment are shown in Fig. 4. It consists of a gamma-ray source, shielding material, and a detector. In an environment with minimal density (air, polyurethane foam), the shielding material prevents photons from reaching the detector directly. If the assembly is applied to a higher density material (e.g., water), then due to Compton scattering, the gamma rays are deflected from the source through the surrounding material to the detector. The absorption of gamma rays is directly proportional to the average density of the surrounding medium in the emitter-detector path.

The development of a small-diameter probe with a small range requires the verification of a different measurement structure than is commonly used. A piece of pitchblende from the Faculty of Science of Charles University collections was used as the first experimental emitter. Based on these successful tests, in June 2015, the Aquatest Drill logging Department (now Geotechnika) ordered the production of one probe for measuring the grouting of ground heat pump exchangers. The Aquatest/Geotechnika staff supplied special gamma shielding material and purchased a 137 cesium gamma radiation (300 MBg) source to produce the probe. The source of the appropriate intensity was selected based on the experiments on the test site at the Aquatest/Geotechnika technical site in Nučice. Based on the test experience, a 15 mm-diameter, 28 cm-long GGL probe (Fig. 4) with a gamma-ray detector based on the SBM-21 miniature Geiger–Muller tube

Fig. 4 Small diameter probe on GGL. 1: emitter; 2: shielding; 3: detector

(https://www.pocketmagic.net/tube-sbm-21-miniature-geiger-muller/) was completed and calibrated to the required densities in 2017.

The principle of this method requires the use of a powerful gamma-ray source, which is legal to possess in EU countries with proper permits only. In the Czech Republic, all permits under the Atomic Act are required to handle ionizing radiation sources (Act ČR No. 263/2016 Coll 2016). This approach applies not only to the actual handling of the emitter (tests, forms) and its transport (dangerous goods—ADR transport) but also to the strict conditions imposed on the packaging of the emitter (special containers) and its storage (special shielded rooms). Moreover, the acquisition of radioactive isotopes is costly (Fig. 5).

Measuring the natural temperature gradient of the Earth's landmass

The measurement of the natural vertical thermal gradient of the Earth's mass, among other things, is commonly applied to the flow of water through a borehole as part of carottage measurements (Clauser and Mareschal 1995). Thermometry, therefore, is the second most commonly used method in combination with gamma–gamma-ray logging to check the quality of casing seals. The average natural thermal gradient in the Bohemian Massif region is 2–3 °C per 100 m of depth (Schinkman 2010). The flowing water in the borehole disrupts this gradient. Since boreholes for heat pumps are dug to similar depths on the order of the first 100 m (Ingersoll and Plass 1948), measuring the natural thermal gradient is an easily measurable guide to the quality of ground heat exchanger grouting. For temperature measurements in boreholes, a thermometer working in hundredths of a degree Celsius was produced in earlier years in private practice. The temperature measurements were based on a semiconductor sensor developed in the 1980s

Fig. 5 Ground heat exchanger pipe thermometer

for satellite instruments under the Interkosmos program. With resistances in the kilo-ohm range, the sensors have linear characteristics over the applicable temperature range (0–40 °C) and low-temperature noise. The sensor itself was watertight and housed in an 8 mm-diameter brass tube with a length of 100 mm, among other things, forming the necessary ballast for embedding in the pipe. The thermometer was approximately set to measure between 0 and 40 °C using a calibrated thermometer with a division of 0.1 °C. However, developing new thermometers to measure the temperature in borehole exchangers for heat pumps is unnecessary. Suitable commercially available thermometers with an accuracy of tenths to hundredths of degrees Celsius are included in some probes for measuring water levels in boreholes. The diameter of these probes was less than 16 mm (Fig. 6).

Induced thermometry

When testing small-diameter GGL probes and thermometers, it was possible to verify the temperature curves during the cooling of heated rock masses by water flowing between hydrogeological aquifers connected by a borehole (May 2018). In practice, this approach involves a combination of the liquid tracer dilution method used in carottage (Maurice et al. 2011) and the so-called TRT test equipment (similar to the hydrodynamic test on borehole exchangers for heat pumps) ((Gehlin 2002), 11, part 5; chapter 8.3; July 2020).

During the measurement, the surrounding rock mass is heated for approximately the first hour with the help of a ground heat exchanger. Once the heating of the rock mass is complete, the actual measurement of the vertical distribution of temperature in one tube of the earth exchanger starts. In a well-designed earth exchanger, the temperature

Fig. 6 Level gauge with thermal sensor

should drop uniformly. In the area with cracked grouting, groundwater flows around the exchanger tubes. When this occurs, very rapid cooling occurs, or a flow of water in the borehole outside the exchanger tubes can be observed in the distribution of temperature over time.

The idea was implemented in a device with a thermal capacity of 3 KW (derived from a maximum current of 16 A in a 250 V socket). The core of the device was a commercially sold direct heating system with an input of ~ 3 KW (https://www.dzd.cz/en). A self-priming circulating pump with a discharge capacity of ~ 1 l/s and a maximum discharge height of 42 m was used to circulate the water in the ground heat exchanger. The system (Fig. 7) was able to heat the rock mass in the vicinity of the borehole from ~ 8–25 °C in an hour under the conditions of the eastern and western parts of the Bohemian Cretaceous Basin.

Acoustics/seismic

During the test measurements, it was found that the heat exchanger pipes affected by the hydraulic short circuit were buzzy and humming, even when the ground heat exchanger technology and the installed heat pump were switched off. The nature of the problem implies that boreholes with significant hydraulic short circuits, where water is discharged into the air, exhibit typical acoustic behavior due to the impact of droplets on the water surface, i.e., 'fizzing'. Similarly, ground exchangers with water overflowing above the ground have a similar "hum", where the ground exchanger design and the water flow cause turbulent flow in the borehole. Both an electret microphone and a geophone from the GEO SPACE type PAT-45S4698 were connected to a microphone preamplifier which were used to detect the acoustic manifestations of the earth exchangers. The sound recording was recorded on a standard laptop computer.

Fig. 7 Induction thermometry device with a heat output of 3 KW

The problem with such measurements is background acoustic and seismic noise. Measurements cannot be made under strong winds or in places near busy traffic (roads, railways). The advantage of the measurement system should be that a defective ground exchanger can be detected even through a layer of material (ground, concrete). Detection of defective ground exchangers through the material has yet to be tested.

Explosive charges for blasting

In 2018, experimental blasting of plastic pipes took place on the premises of Explosia a.s. Based on these experiments, Semtex (https://explosia.cz/app/uploads/2017/11/Explosives-catalog-2017.pdf) plastic blasting charges were developed to enable safe blasting work in the pipes of earth exchangers in the intramural areas of municipalities. Semtex explosive was used because of its high detonation velocity (7 km/s) and small detonation diameter (5 mm). The developed charge, weighing 150 g to 200 g, is equipped with a weight for easy insertion into the exchanger pipe (Fig. 8) and a device to reliably cut the wire for detonation (principle of the Stringer anti-aircraft missile warhead). The problem with such a developed charge is that it requires approval for blasting in the Czech Republic (Act ČR No. 61/1988 Coll 2024). It takes about a year to process the approval. Currently, experiments are underway using the Pyrotechnic compositions that are used in fireworks (Fig. 9). The construction of the Pyrotechnic charge is similar to that of the Semtex charge. Due to the different physical actions of the Semtex and Pyrotechnic compositions, the need to cut the wire to detonate the explosive is eliminated.

Fig. 8 Semtex charge design

Results of measurements at the sites

Identification of the sites where measurements of the quality of the ground exchangers could be made was the major problem. For obvious reasons, no drilling company wanted to verify that their constructed ground heat pump exchangers showed no signs of hydraulic short circuiting. In the spring of 2018, houses were constructed with projected heating by heat pumps east of Prague near the village of Nebřenice. Here, for the first time, we had the opportunity to verify the quality of the work associated with the construction of ground heat exchangers for heat pumps in the rocks of the Štěchovice Group of the Barrandien Proterozoic (Knížek 2013). The measurements also included verification of the grouting quality with a small-diameter probe on the GGL. The exchangers selected by the construction company were measured before and after grouting. Also interesting were the measurements of exchangers not "selected" beforehand. The results are shown in Figs. 10 and 11. From the pictures, at the first glance, it is clear that some heat exchangers were insufficiently grouted. Given the obtained results, the measurements were terminated by the responsible construction personnel.

The measurements verified the possibility of inspecting ground heat exchangers using a small-diameter GGL probe. The measurements also validated the assumption that there was an obvious primary error in the actual borehole grouting technology and the materials used for heat exchangers for ground heat pumps. Figures 10 and 11 clearly show that in areas with groundwater flow, the grouting mixture is being washed into the rock mass. Since the certified grouting mixture consists of cement, clay, micromilled mica, and micromilled sand, it is obvious that its sealing function must inevitably fail in areas with fractured systems containing flowing water.

Fig. 9 Experimentally ruptured PE pipe, left from the Semtex charge, right from the pyrotechnic charge

Measurements with a small-diameter GGL probe were also verified in Kuks, a village in the Bohemian Cretaceous Basin. Here, due to insufficient grouting of the ground exchanger, there was a loss of water in the spring, which supplied water to the village.

A small-diameter GGL probe was used to measure all four heat exchanger pipes. The drilling company's management argued that the measurement of the density of the grout in the heat exchanger pipes did not prove the flow of water through the borehole. Thus, the natural thermal gradient of the ground was also measured at the borehole. After the natural gradient measurement, the mass was heated by an induced thermometry apparatus ("Induced thermometry") to ~ 15 °C. This temperature difference was sufficient to verify that water flow occurred in the borehole outside the heat exchanger tubes in

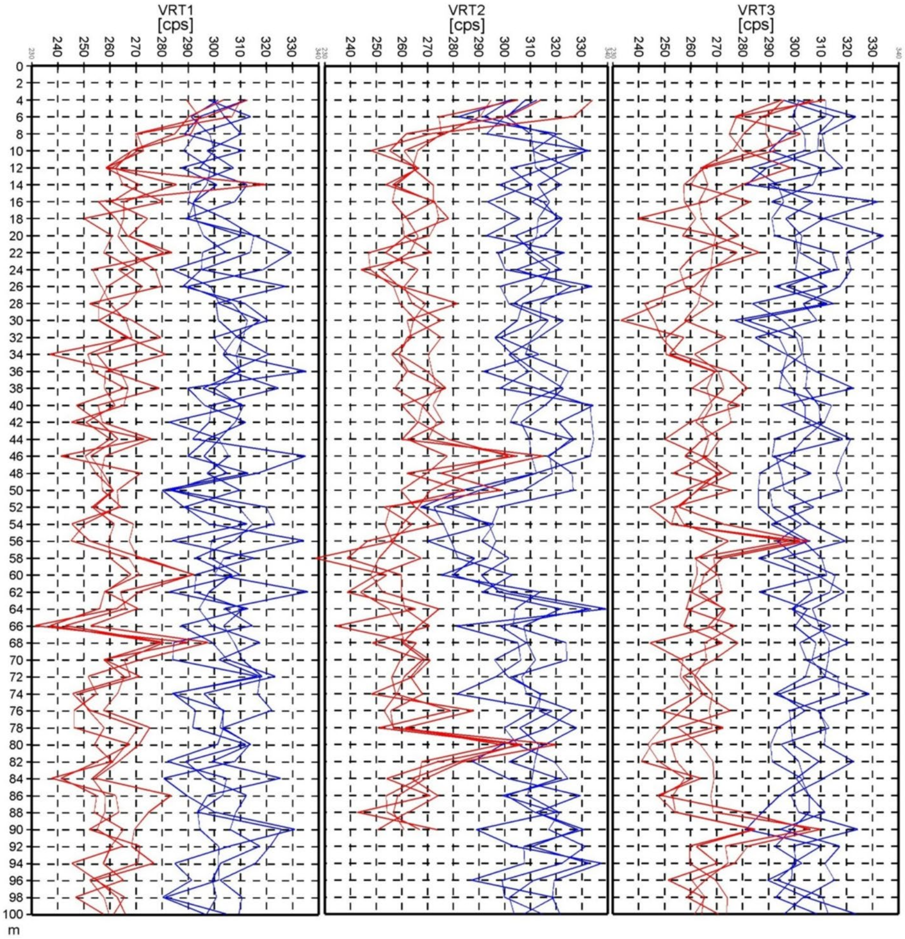


Fig. 10 Measurement results of the GGL from selected boreholes near Nebřenice (a village near Prague). The blue lines denote measurements in four pipes before grouting; the red lines denote measurements in the same pipes after grouting. Values less than 270–280 counts/s can be regarded as areas with high-quality grouting, and values greater than 290–300 counts/s correspond to nongrouted areas. In borehole 2, at depths ranging from 44 to 52 m, a fallen drilling crumbling (52–60 m) and a tectonic fracture noticeably affected the cavern. Measurements in borehole 3 indicated an interrupted column of the grouting material at 56 m and 90 m depth. This phenomenon has also been observed in other boreholes

the nongrouted part of the borehole. The measurements were already conclusive and showed that the borehole was not sufficiently grouted. The measurements, together with the lithology, are shown in Fig. 12. Figure 12 shows that water flows through the borehole (water from the first fractured aquifer flows outside the pipes) at depths ranging from 28 to 36 m (the water level in the borehole is ~ 36 m) and seeps into the fractured aquifer at intervals ranging from 36 m to ~ 50 m. The presented measurements were verified during borehole rehabilitation.

Methods for measuring ground heat exchangers were used in June 2022 to detect water intrusion through two overflowing boreholes into Quaternary sediments in the village of Černěves. The first borehole did not show any signs of anomalous behavior; however, at the second borehole, an overflow of ~ 3 l/s was observed between the exchanger tubes (Figs. 13, 14). The natural thermal gradient measurement method was used first (Fig. 15). It was already apparent from the results of these

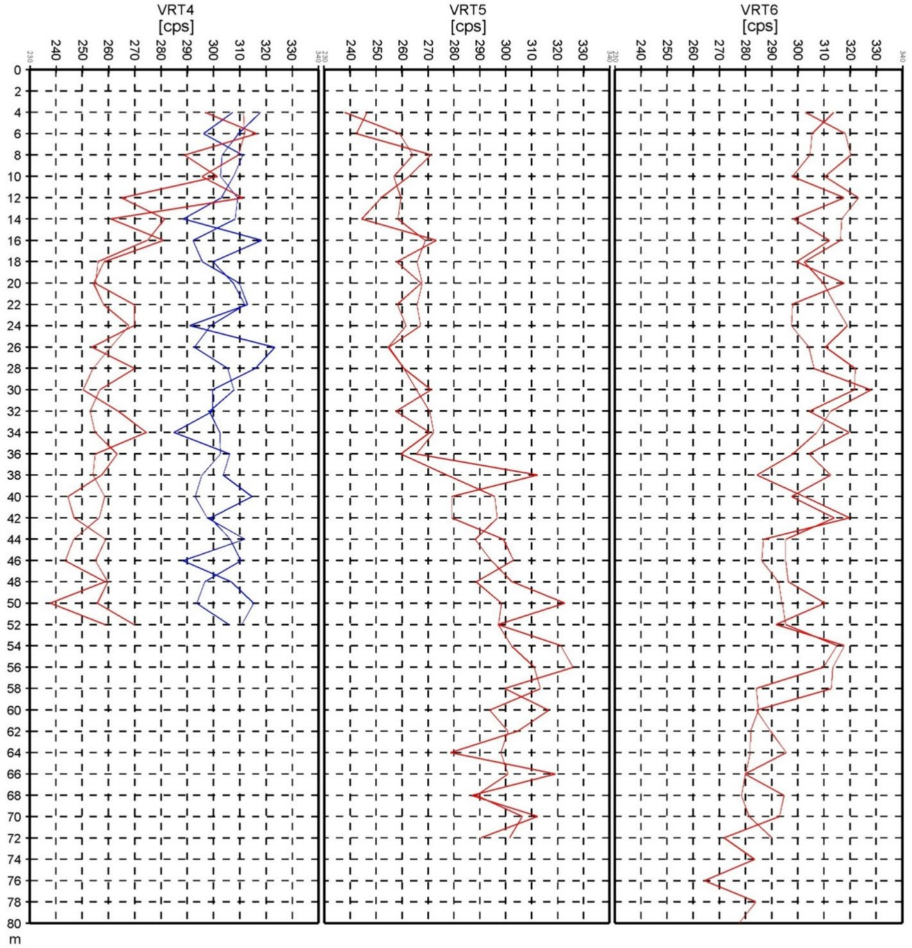


Fig. 11 Measurement results of the GGL at a location near Prague (Nebřenice) from not selected 100 m deep boreholes (behind the builders' backs). The blue lines denote measurements before grouting; the red lines denote measurements in the same pipes after grouting. Values less than 270–280 counts/s can be regarded as areas with high-quality grouting, and values greater than 290–300 counts/s correspond to nongrouted areas. Like boreholes 1–3, borehole 4 also exhibited problems with grouting down to a depth of ~ 14 m. Borehole 6 was not grouted down to a depth of ~ 60 m, while borehole 5 was missing grouting from 38 m below

measurements that water was flowing through both boreholes. In the first borehole (CSN), water percolates into the Quaternary sediments. According to experience at the site near Louny, which has a similar geological structure, this situation is unsustainable. Groundwater will flow to the surface after a few years due to the colmatization of gravel sands (Fig. 16). The colmatation (clogging) of gravelly sands is caused by the oxidation of iron oxyhydroxides and by microorganisms living in groundwater. Iron oxyhydroxides and microorganisms gradually fill the pores in the Quaternary sediments around the borehole due to overflow. The oxyhydroxides have greater magnetic permeability than does the gravel. The distribution of oxyhydroxides around the borehole can therefore be monitored by GPR. This was demonstrated by an experimental GPR measurement carried out by the G-impuls Company (Fig. 17).

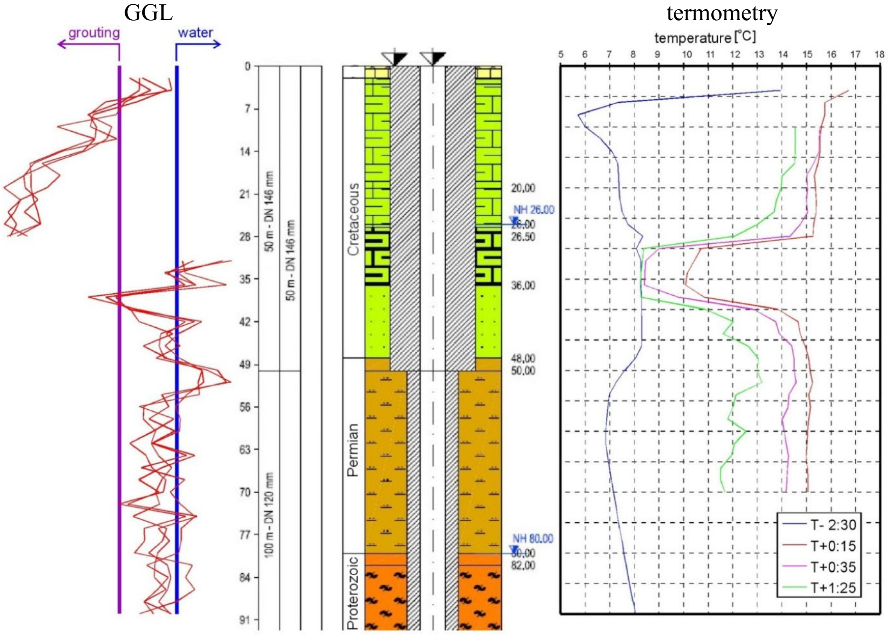


Fig. 12 Borehole measurements at Kuks. On the gamma–gamma-ray plot (red curve on the left), an area with grouting is marked (to the left of the purple line); the nongrouted area in the borehole can be deduced from a curve located to the right of the blue line. The temperature (a chart on the right) at T-2:30 was measured before heating the massif, and the temperatures at T + 0:15 to T + 1:25 were measured after 1 h of heating the rock massif by a heat output of 3 kW

Fig. 13 Overflow of ~ 3 l/s in the village of Černěves

Fig. 14 Consequences of groundwater overflow

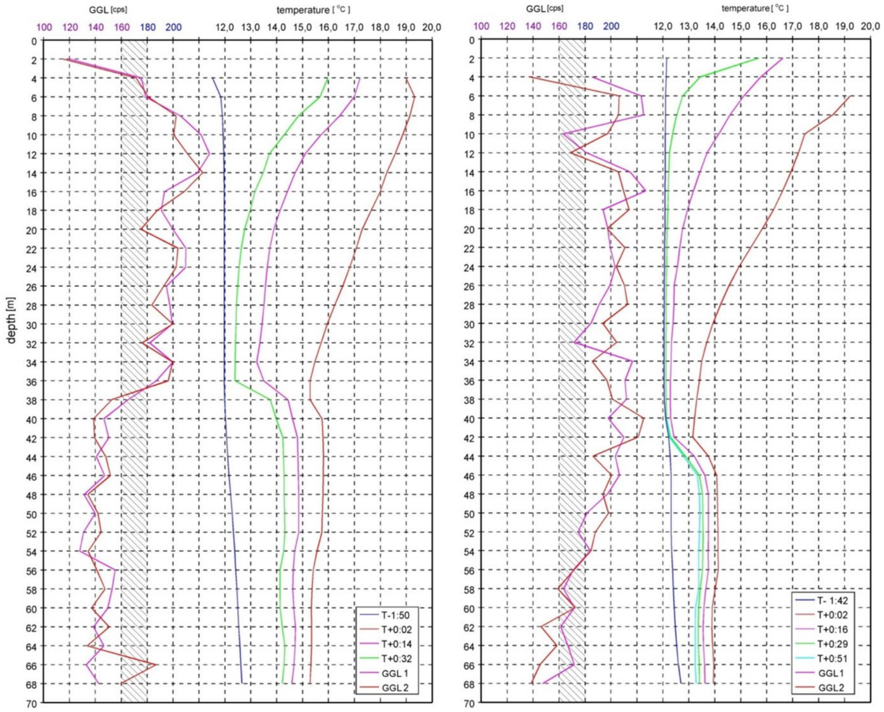


Fig. 15 Measurement results in June 2022; the left panel shows the borehole CSN, and the right panel shows the borehole CST (see Figs. 13, 14)

Fig. 16 Overflow of ~ 2 l/s in the village of Louny

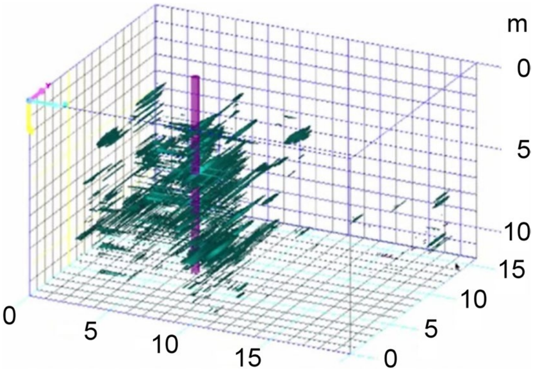


Fig. 17 Distribution of iron oxyhydroxides in the vicinity of the borehole in Louny (borehole in purple, iron oxyhydroxides in gray, GPR measurements by G-impuls company)

The method of induced thermometry at the Černěves location confirmed the first thoughts about defectively injected wells (Fig. 15). Vertical movement of water toward the surface can be observed in the curves of the CSN and CST boreholes. The results of the temperature measurements were also confirmed by the gamma–gamma well-logging method, where two opposite pipes of the ground exchanger were measured (GGL1 and GGL2; the hatched area indicates the area of uncertainty in the method used, i.e., the area where it cannot be determined whether the borehole is well grouted). The CSN borehole was injected only to a depth of 36 m. In the CST borehole, grouting was confirmed only below a depth of 60 m. In the depth interval from 44 to 60 m, there was a filling of rocks (probably gravel-sand) in the borehole.

Measuring the thermal gradient in a ground heat exchanger requires approximately half an hour. The possibility of fast detection of hydraulic short circuits using acoustic manifestations in the borehole was tested at the site in Černěves. The values were evaluated on-site by only hearing. For publication of the acoustic manifestations (Figs. 18, 19), two sets of measured values were used. The measurements before and after grouting the borehole without overflow (CSN) show that after grouting 1.5 m^3 of concrete into the ground exchanger, the overflow stopped.

Repair of defective ground heat exchangers for heat pumps

In practice, this approach includes not only the detection of defective grouting in boreholes for ground heat pump exchangers but also the possibility of correcting the detected lack of grouting. When a borehole is drilled into a hard rock mass on a property outside a building, it is not difficult to re-drill the borehole for the ground heat exchanger or to reequip and re-grout it. PE pipes grouted with often very soft cement–clay mixtures are softer than granite or amphibolite. However, this situation is worse for heat exchangers installed under a building's foundation or boreholes in sedimentary rocks,

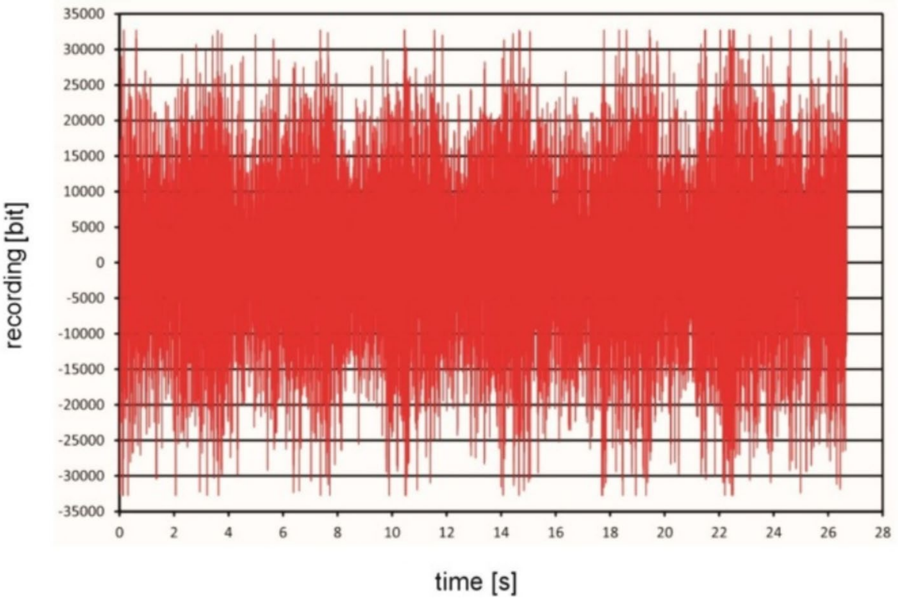


Fig. 18 Acoustic manifestations at the CSN well before grouting (geophone record)

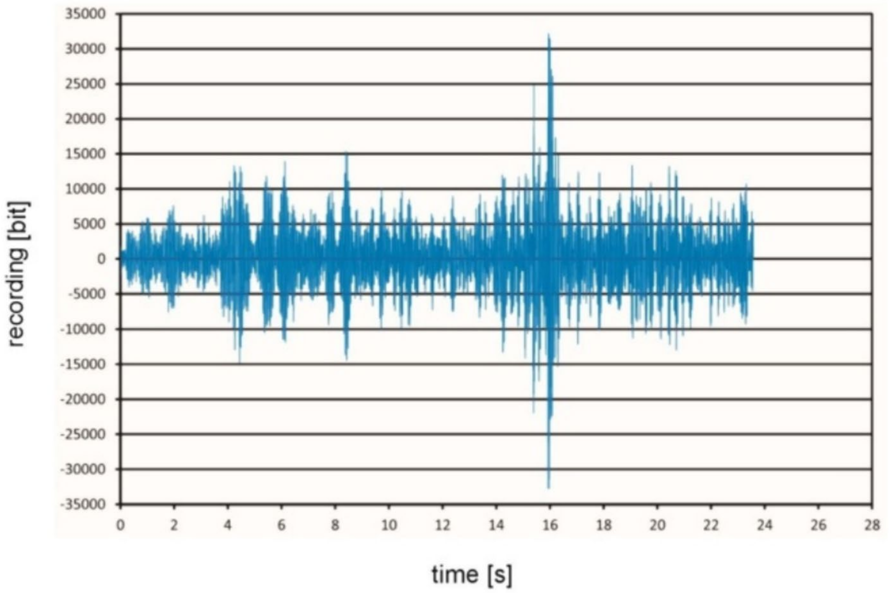


Fig. 19 Acoustic manifestations at the CSN well after grouting (geophone record)

where even the mere presence of plastic PE pipes often represents a significant increase in the strength of the rock mass. The presence of tectonic faults significantly complicates remediation interventions in borehole exchangers. There is a high probability that the drilling tool will move out of the original borehole while attempting to re-drill a ground heat exchanger for a heat pump. This approach will create two problems, both of which are difficult to handle. Therefore, perfect knowledge of the geometry of the area outside the installed pipes, including the groundwater flow, is a prerequisite for the disposal of poorly grouted boreholes for ground heat pump exchangers. This information can currently be obtained using the above-mentioned measurement methods.

In 2019, remediation was carried out in the village of Kuks to prevent vertical groundwater flow in boreholes fitted with ground heat pump exchangers. Two identical boreholes were excavated and drilled at the site. Although only one borehole was measured (Fig. 12), it was reasonable to assume that the results of the GGL, natural temperature gradient, and induced thermometry measurements would also be identical. To avoid possible problems with redrilling the original boreholes in soft inhomogeneous material (tectonically fractured friable sandstones of Cenomanian age), the possibility of grouting the heat pump boreholes with the inside of the installed ground heat exchanger pipes was tested at Kuks.

The PE pipes installed at Kuks with an inner diameter of 25 mm were perforated in the areas of lithological transitions with the developed Semtex charge. The boreholes were progressively grouted through the holes created by the blasting operations. The boreholes are being rehabilitated in the Crystalline and Permian areas with a volume of grout equivalent to the volume of the borehole. In the Cenomanian sandstones, the effects of the observed tectonic fault were evident, and 6 m^3 of grout had to be grouted into the two boreholes with a 25 mm-diameter pipe (first borehole 2 m^3, second borehole 4 m^3). Work at the site was completed with the observable onset of groundwater levels on 18

Fig. 20 Spring overflow in the village and water in the second spring on 24 October 2019

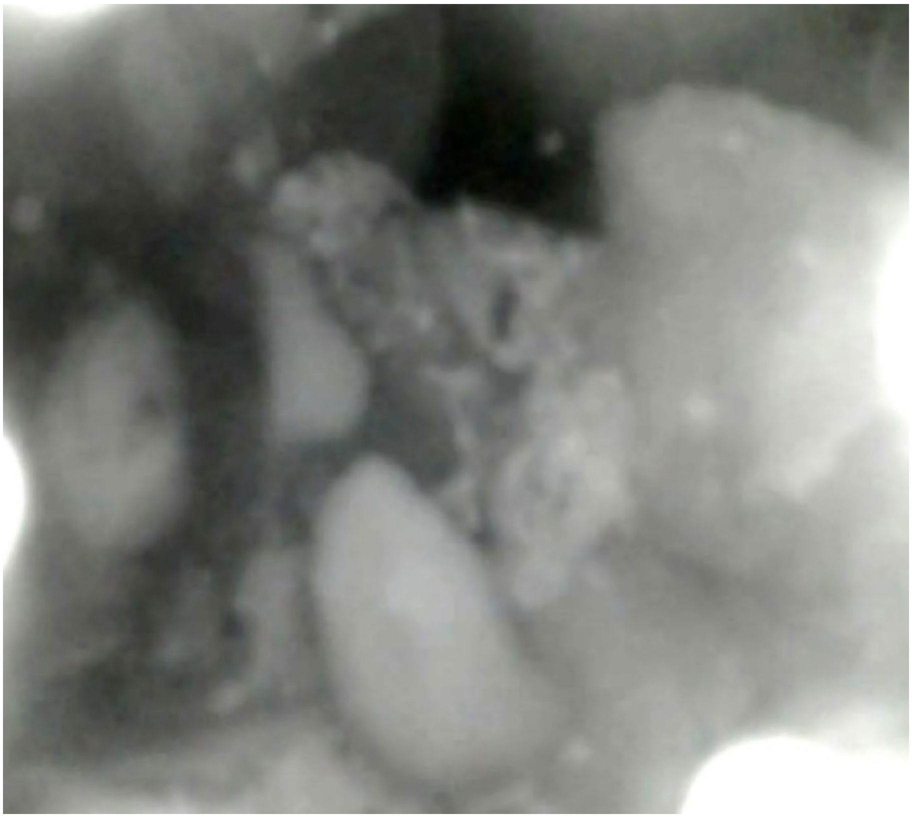


Fig. 21 Area of the hole (up) in the pipe of the ground heat exchanger (inner diameter 25 mm) at a depth of 40 m

October 2019 (one perforated exchanger pipe was used to monitor groundwater levels). On 23.10.2019, the residents of the surrounding area registered the onset of water levels in their wells, and a day later, the exploited spring overflows in the village were recovered (Fig. 20).

A similar procedure was adopted for the Černěves site. One pipe of the ground exchangers was perforated at a depth of 34 m (borehole CSN) and at a depth of 40 m (borehole CST) with a body containing 10 g of pyrotechnic composition (Fig. 21). The second pair of pipes was left unperforated, in contrast to the procedure at the village of Kuks. After grouting 1.5 m^3 (well CSN) and 2.2 m^3 (well CST) with concrete, the overflow from the intercepted aquifer stopped. In the case of the CST borehole, overflow was visible immediately after the remediation intervention, while in the CSN well, it was verified acoustically (Figs. 18, 19). After overflow remediation, pressure tests were successfully applied to the remaining pairs of nongrouted ground exchanger tubes. After the pressure tests, the ground exchangers were connected to the heat pump (Fig. 22).

Discussion

Previously used methods of measuring boreholes for ground heat exchangers of heat pumps using classical well-logging methods and probes with diameters of ~ 40 mm did not allow us to measure the quality of grouting after completion of the boreholes. Using the proposed measuring instruments and methods, caverns and groundwater flow can be detected in areas outside the ground exchanger tubes. The measurement systems used are very fast and require little technical equipment. In contrast to the already used method of injection with ferromagnetic materials, the use of a small-diameter GGL probe is indifferent to rocks with higher magnetite content (basalts, metabasalts). Considering the construction time of a borehole for ground heat exchanger ~ 1 day, the time of the proposed measurement is negligible. An acoustic inspection of the system already in operation, including installing geophones lasting a few minutes, will help to detect the largest hydraulic short circuits that significantly threaten the groundwater quantity at the site. Implementing tested control systems will help to minimize the environmental damage caused by the defective construction of ground heat pump exchangers.

Fig. 22 Cerneves site July 2023. Top right: inlet to the technology (see Figs. 13, 14)

Measurements of the grouting quality of the ground heat pump exchangers also confirmed the assumption that there is an apparent primary flaw in the actual borehole grouting technology and materials used. It is clear that in areas with groundwater flow in fractured systems, the grouting mixture is being washed into the rock mass. Since the certified grouting mixture consists of cement, clay, micromilled mica, and micromilled sand, it is obvious that its sealing function inevitably fails in areas with fractured systems containing flowing water. In small-diameter boreholes, the rest of the grouting is held in position by the borehole equipment, defining the pipes in relation to the walls (centralizers). As a result, the loss of the grouting compound is not visible on the surface.

The grouting compound used to rehabilitate ground heat pump exchangers was based on the original grouting compound supplied or cement with the addition of sand. Drilling companies inject ground heat exchangers with dense mixtures using pressure piston pumps. The 0.1/1 or 0.1/0.5 grit sand used in the remediation process should not be conveyed into the borehole with the grouting mixture through piston pumps (this would cause the pumps to jam). During remediation, diluted mixtures were mixed with sand conveyed into the borehole via a WQ3-24-0.75 pump (0.1/1 sand) or even with an SQ 2/85 Grundfos pump (0.1/0.5 sand only).

During the study, some fraudulent practices by drilling companies were also uncovered; for example, when they detect grout loss caused by technological discipline, they add dry grout to the borehole, which sticks to the wet walls. This masks the loss of grout. Using cheap uncertified grouts produced by drilling companies is also a cause of concern (some of these grouts breakdown in water).

The proposed rehabilitation system of opening one pipe of the ground exchanger and subsequently adding the concrete grouting mixture into the borehole is significantly more reliable, less expensive, and more economical than the currently used system of redrilling the already completed work. In the case of Kuks, the original borehole exchangers were disposed of using the new repair technologies proposed; both the remediation of the rock environment and the salvage of the constructed exchangers have already been achieved in the village of Černěves. The proposed system of measuring and remedying ground heat pump exchangers will certainly contribute to better groundwater protection in the use of geothermal energy.

Conclusion

The developed methods for measuring the quality of grouting and rehabilitation of boreholes for ground heat exchangers of heat pumps allow for the measurement and rehabilitation of already built heat exchangers even under the foundations of buildings without the need for significant construction interventions or the arrival of heavy equipment. According to the results of the measurements carried out between 2018 and 2023, it would be possible to enforce massive quality control of the grouting of heat exchangers for ground heat pumps. Technically, a simple measurement of the temperature of the natural gradient in a ground heat exchanger should become the basis for permitting its operation. The above procedure is currently implemented in the standard VDI 4640 ((VDI 2024b), part 5, chapter 8.3, July 2020) of the Federal Republic of Germany.

If the natural gradient is disturbed by groundwater flow, it is possible to proceed to a more detailed measurement using induced thermometry and the GGL method. Due to the poor quality of drilling carried out in constructing heat exchangers for ground heat pumps, the proposed measurement system can eliminate any possibility of groundwater loss to deeper aquifers to the maximum extent possible. It can be assumed that fraud will also occur in massive measurements of natural thermal gradients in ground heat pump exchangers (similarly, fraud occurs in hydrodynamic tests on boreholes when a hydrogeologist applies curves from previously measured sites). Nevertheless, the proposed measurements will allow a preliminary check of the grouting quality of ground heat pump exchangers in most of the cases.

Author contributions

Petr Nakládal: initial idea and overall concept, fabrication of instruments, field measurements and data processing, and writing the paper. Martin Procházka: funding of the GGL probe and assistance with measurements at the sites. Viktor Goliáš: first experiments at Charles University, professional help with the text outline. Jaromíra Hrdá: data processing, revision of text, and help with publication.

Funding

Research and implementation were privately funded.

Availability of data and materials

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

We confirm that this manuscript is original and has not been published elsewhere in this field, nor is it being considered for publication elsewhere.

Consent for publication

The author and all the coauthors declare their consent to the publication of this article.

Competing interests

The author and all the coauthors declare that they are not aware of any competing financial interests or personal relationships that might influence the work presented in this paper.

Received: 27 September 2023 Accepted: 4 September 2024

References

Act ČR No. 61/1988 Coll. Act of the Czech National Council on Mining, Explosives and State Mining Administration. 2024.

Act ČR No. 263/2016 Coll. Atomic law; and Decree No. 422/2016 Coll. Decree on radiation protection and security of the radionuclide source. 2024

Claesson J, Hellström G. Analytical studies of the influence of regional groundwater flow on the performance of borehole heat exchangers. In: Proc. of the 8 th International Conference on Thermal energy storage, Terrastock 10. 2000, Stuttgart, Germany.

Clauser C, Mareschal J-C. Ground temperature history in central Europe from borehole temperature data. Geophys J Int. 1995;121(6):805–17.

Congedo PM, Colangelo G, Starace G. CFD simulations of horizontal ground heat exchangers: a comparison among different configurations. Appl Therm Eng. 2012;33–34(2):24–32.

Corson L, et al. Field validation of a detectable, magnetic, cementitious grout for rock fracture grouting. Int J Rock Mech Mining Sci. 2021;145:104853.

Di Raimondo G. Production of geothermal energy at Larderello. RGELA Rev Gen Electr (France). 1955;64(8):373–90.

DiPippo R. Principles, applications, case studies and environmental impact. In: Geothermal power plants. 2012. ISBN 978-0-08-098206-9.

Ericsson LO. Värmeutbyte mellan berggrund och borrhål vid bergvärme-systém (heat exchange between crystalline bedrock and borehole in an energy well system). Department of Geology, Chalmers University of Technology and University of Göteborg. Publ. A 52. Göteborg, 1985, Sweden. (In Swedish).

Gehlin S. Thermal Response Test, Method Development and Evaluation. Department of Environmental Engineering Luleå University of Technology SE-971 87 Luleå, 2002 Sweden. 2002. https://www.diva-portal.org/smash/get/diva2:991442/fulltext01.pdf.

Ingersoll LR, Plass HJ. Theory of the ground pipe heat source for the heat pump. Heat Piping Air Cond. 1948;7(1948):119–22.

Jakub S. Processing of temperature logging data in the area of the Ohárecký lineament (diploma thesis). Faculty of Science, Charles University, Prague, 2010.

Kayaci N, et al. Experimental and numerical investigation of ground heat exchangers in the building foundation. Energy Convers Manage. 2019;188(5):162–76.

Knížek M. Radial tectonics of the Barrandien (Dissertation). Masaryk university of natural science Brno, Institute of Geological Sciences, 2013.

Mareš S, Hrách S, Marek F, Matolín M, Válek R. Introduction to applied geophysics. Technical Literature Publishing House, Prague. 1979, p 590.

Maurice L, Barker JA, Atkinson TC, Williams AT, Smart PL. A tracer methodology for identifying ambient flows in boreholes. Ground Water. 2011;49(2):227–38.

Muraya NK, O'Neal DL. Interference of adjacent legs in a vertical u-tube heat exchanger for a ground coupled heat pump. Soc Heating. 1996.

Reynolds RC Jr. Estimation of mass absorption coefficients by Compton scattering: improvements and extensions of the method. Am Mineralog. 1967;10(52):9–10.

Sarbu I, Sebarchievici C. General review of ground-source heat pump systems for heating and cooling of buildings. Energy Build. 2014;70(2):441–54.

Shonder JA, Beck JV. Determining effective soil formation thermal properties from field data using a parameter estimation technique. ASHRAE Trans. 1999;105(1):458–66.

VDI (Association of German Engineers) guidelines of the Federal Republic of Germany; VDI 4640, parts 1–5 2024a.

VDI (Verein Deutscher Ingenieure)—richtlinien der Bundesrepublik Deutschland; VDI 4640, blatt 1 bis 5. 2024b

Zarrouk SJ, Moon H. Efficiency of geothermal power plants: a worldwide review. Geothermics. 2014;51(7):142–53.

Publisher's Note