European project “Cheap-GSHPs”: installation and monitoring of newly designed helicoidal ground source heat exchanger on the German test site

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Abstract
Nowadays, the energy price fluctuations and the economic crisis are jeopardizing the development and diffusion of renewable technologies and sources. With the aim of both reducing the overall costs of shallow geothermal systems and improving their installation safety, an European project has took place recently, under the Horizon 2020 EU Framework Programme for Research and Innovation. The acronym of the mentioned project is Cheap-GSHPs, meaning “cheap and efficient application of reliable ground source heat exchangers and pumps”; the Cheap-GSHPs project involves 17 partners among 9 European countries such as Belgium, France, Germany, Greece, Ireland, Italy, Romania, Spain and Switzerland. In order to achieve the planned targets, a holistic approach is adopted, where all involved elements that take part of shallow geothermal activities are here integrated. In order to reduce the specific costs of geothermal installations, some newly designed geometries of heat basket-type ground source heat exchanger (GSHE) are modified drastically to receive a better performance of the geothermal installation. Within the sector of very shallow geothermal systems, these new developments are also tested on six representative demonstration sites around Europe. At the German test site in Northern Bavaria, four heat basket-type GSHEs are installed and equipped with certain monitoring systems (moisture, two different temperature sensors) and various backfilling materials of different grain size classes. The different installations will be tested for 12 months to evaluate the best combination of the newly designed heat basket-type GSHE and corresponding backfilling material mixture.

Keywords Very shallow geothermal energy · Backfilling material · Monitoring · Renewable technologies

Introduction
Nowadays, geothermal energy is one of the most seminal sources due to its high potential and multiple uses. With the aim of both reducing the overall costs of shallow geothermal systems and improving their installation safety, an European project takes place recently, under the Horizon 2020 EU Framework Programme for Research and Innovation. Cheap-GSHPs project involves 17 partners among 9 European countries such as Belgium, France, Germany, Greece, Ireland, Italy, Romania, Spain and Switzerland. In order to achieve the planned targets, a holistic approach is adopted, where all involved elements that take part of shallow geothermal activities are here integrated. Due to the fact that the technical feasibility, the total performance and installation costs are affected enormously by underground properties, it is indispensable to have detailed information about these parameters. Within this project, a new helicoidal-type
ground source heat exchanger (GSHE) was developed to combine the advantages of smaller diameter drillings and the higher pipe volume per metre depth compared to standard closed-loop systems as single-U or double-U probes which are also coupled to a heat pump to extract the geothermal energy from the underground (Omer 2008). Additionally, the cost–benefit performance of various backfilling materials should be scrutinized. Some natural backfilling materials are used to provide the best thermal conductivity between the GSHE and the original soil body. Therefore, not every backfilling mixture is suitable as thermal conductivity depends on texture, water content, temperature and mineralogy of the material (Farouki 1981; Hiraiwa and Kasubuchi 2000; Gonzalez et al. 2012; Nikiforova et al. 2013). Also the coastal part for the natural basic components is differing: for example, 1 tonne of loose washed sand, 0–2 mm in grain size, is 15.71 € without VAT and transport. Sand has a low water retention capacity; therefore, the thermal conductivity is very depending on the saturation of the pore volume. By adding fine-grained material, the water retention capacity can be enhanced which also improves the thermal conductivity of the material (Bertermann et al. 2015). For comparison, 1 tonne of clay powder is 63.50 € without VAT and transport, and 1 tonne (in 25-kg bags) of bentonite is 329 € without VAT and transport.

An improving combination of these natural products could provide a better thermal performance if used as backfilling material for GSHEs. One major aim is to save costs without impairing the heat extraction rate of the shallow geothermal system. Therefore, a new drilling technique is tested on the Cheap-GSHPs test field in Erlangen, Germany, to complete a safe, fast and cheap installation of the newly developed GSHEs with different geometries as standard products.

Test site

The test site is located in Erlangen-Eltersdorf (Lat: 49.54387; Long: 10.98535), which is located in the alluvial Regnitz river valley, in Northern Bavaria. The area of the test site is delimited in the north by the Main River Valley, in the west by the middle Triassic Gipskeuper and in the south and east by the Jurassic Swabian/Franconian Alb. The Regnitz valley itself and the sediments at the test site show fluvial sedimentation of medium- to fine-grained deposits. The stratigraphy is defined by an alternation of medium (sand)- and fine-grained material (silt and clay). Due to the appearance of random clay lenses, a horizontal homogeneous consistency of the stratigraphy does not exist. The four helicoidal GSHEs were installed in an upper Triassic sequence of sand, sandy claystone and weathered sandstone. The GSHEs are situated on the premises of the REHAU AG + CO company with a mutual spacing of three metres. The exact location is illustrated in Fig. 1, and the GSHEs are arranged as listed in Table 1.

Materials and methods

Helicoidal GSHE + sensors

In all four boreholes a newly designed helicoidal GSHE called RAUTITAN New Helix is installed. The basis for the design was the marketable RAUGEO Helix PE-Xa. This spiral heat basket-type GSHE was within portfolio of REHAU for several years. A common installation has to be realized using an excavator for trenching and also for the creation of the borehole which had to have a diameter of minimum 420 mm. The final installation depth of this “classical” helix is from 5 to 6 m depth (REHAU AG + CO 2012). The parameters of the New Helix differ from the standard product at selected point: The inlet flow is manufactured from a co-extruded RAUTITAN single helix. The pipe, with a total length of 25 m, is multilayered and consists of PE-Xa/aluminium/PE material. The cold-winded, 25 × 3.7 mm stable pipe is produced by REHAU AG + CO. The return flow is a RAUTITAN 25 × 3.7 mm monolayer PE pipe with a length of 15 m. The connection between the inlet and return flow is ensured via a compression sleeve joining RAUTITAN PX to reach a total pipe length of 40 m. Therefore, also the total installation depth is designed for a borehole depth of 15 m (Psyk et al. 2016). A technical comparison between these two systems is listed in Table 2.

Due to geological circumstances, the GSHE had to be shortened to a final installation depth of 8 m. The diameters of the GSHEs were between 260 and 270 mm. The spacing between the windings varies from 700 to 760 mm. The packaging and transportation are solved in a small, compact geometry which is illustrated in Fig. 2a. Aluminium within the helicoidal part of the GSHE allows the pipe to be extended just on the construction site as it is shown in Fig. 2b.

After enlarging the GSHEs to their final installation length, several measuring sensors were connected to the heat basket to ensure a long-term monitoring. In total, five temperature sensors and three moisture sensors were fixed on each. The temperature sensors (TR) are placed directly at the inlet pipe and along the vertical axis in the centre of the GSHE (TS). The moisture sensors (F) are also placed along the vertical axis of the GSHE. To be able to compare the results of the measurements, all sensor of the same type is intended to be installed at the same depth level. Further the UT is monitored at Borehole #1 for the first five metres depth. The final sensor arrangement is illustrated in Table 3.
The sensors TR1-3, TS1-2 and TU1-6 are 1 mA cable temperature sensors of type Pt1000, a platinum sensor with protection sleeve (Ø 6 × 50 mm) produced out of stainless steel. They were calibrated in order to offset the pull-up resistor and to adjust the cable resistance. The measurement range temperature is between −35 and +105 °C. The sensors F1-3 are soil moisture sensors of the type MAS-1 produced by Decagon Devices, Inc. The sensor measures the dielectric constant of the soil in order to receive information about its water content. Using an electromagnetic field and a microprocessor, the sensor transmits a 4–20 mA current which can be translated into soil’s water content using a calibration function. The

Fig. 1 Location map, geological overview and probe arrangement of the Erlangen test side in Eltersdorf, Bavaria, Germany (Reproduced with permission from Bayerisches Geologisches Landesamt 1971; Google Maps 2017a, b; modified)

Table 1 Adjustments of GSHEs at Erlangen test site

| Borehole | Type               | Number GSHE | Installation depth | Grouting                  | Drilling technique |
|----------|--------------------|-------------|--------------------|---------------------------|-------------------|
| #3       | Helicoidal GSHE    | #04         | 8 m (* 15 m)       | Sand–bentonite mixture    | Auger             |
| #4       | Helicoidal GSHE    | #02         | 8 m (* 15 m)       | Sand–clay powder mixture  | Auger             |
| #5       | Helicoidal GSHE    | #01         | 8 m (* 15 m)       | In situ material          | Enlarged easy drill |
| #6       | Helicoidal GSHE    | #03         | 8 m (* 15 m)       | Building sand             | Auger             |
| #1       | Undisturbed underground temperature (UT) | 5 m       | In situ material | Enlarged easy drill |

Marked with (*) the planned probe dimensions at the Erlangen test site
detectable volumetric water content is between 0 and 100% with an accuracy of ± 6% (Decagon Devices Inc., 2014). However, this paper is especially focused on the temperature sensors as the moisture sensors show now response on the thermal stimulation.

### Table 2 Technical comparisons between RAUGEHO Helix PE-Xa and RAUTITAN New Helix

| Parameter                        | RAUGEHO Helix          | RAUTITAN New Helix          |
|----------------------------------|------------------------|-----------------------------|
| Material                         | PE-Xa                  | Pe-Xa/AL/PE                 |
| Pipe dimension                   | 25 × 2.3 mm            | 25 × 3.7 mm                 |
| Inner tube diameter              | 20.4 mm                | 17.6 mm                     |
| Pipe length                      | 40 m                   | 40 m                        |
| Pipe volume                      | 13.1 dm³               | 9.7 9.7 dm³                 |
| Outer GSHE diameter              | 360 mm                 | 260–275 mm                  |
| GSHE pitch                       | 90–95 mm               | 700–790 mm                  |
| Drilling technique               | Auger (+ casing)       | Enlarged easy drill or standard auger |
| Drilling diameter                | 420 mm                 | 356 mm (inner easy drill)   |
|                                  |                        | 390 mm (Auger)              |
| Density                          | 0.94 g/cm³             | 0.9832                      |
| Thermal conductivity             | 0.40 W/m−1 K−1         | 0.43 W/m−1 K−1              |
| GSHE height (construction condi-| 3 m                    | 15 m (8 m*)                 |
| tion)                            |                        |                             |
| Construction depth               | 1.2–4.2 m              | 0–15 m                      |
| Grouting                         | Excavated material      | Thermal enhanced            |

Marked with (*) the final installed dimensions at the Erlangen test site

![Fig. 2 a, b Unstretched (left) and stretched (right) helicoidal GSHE](image)

In February 2017 the drilling company arrived at the test site in Erlangen-Eltersdorf to drill and install four boreholes of 15 m depth using a newly developed technique and tools. This technique is called *Enlarged Easy Drill*. It includes 1.5-m-long segments with an external diameter of...
355.6 mm. On the outer surface of the tube, a metal spiral with an external diameter of 450 mm has been welded (Fig. 3). Such design avoids the employment of water due to the spiral around the tube. Therefore, the ground is removed out of the borehole by the augers and not by water/mud recirculation. The assembly between the tubes has been designed with male/female connection sleeves welded on the extremity of each tube. Each pair of sleeve has four keys to transmit the torque and two bolts which guarantee the lock in the axial axis among the tubes. This particular design results in an improvement in terms of rod handling, operation and, therefore, in terms of time if compared with a traditional thread connection. For large diameter, the action of coupling heavy tubes with a cylindrical thread could be become very challenging, while in the new design the presence of chamfers on all the edges helps during coupling operation even though the tubes are not perfectly aligned. Another advantage of this design is that the large clamping system, essential for unscrewing the threaded tubes, is no longer required and the investment cost of the machine is reduced.

To remove the tubes after inserting the GSHE, a drilling bit to lose had to be designed. As the bit remains in the underground, manufacturing costs have to be very low; however, on the other hand, the bit has to be qualitative enough to reach the final installation depths. Therefore, the GSHE can stay it the ground, while the tubes are removed out of the borehole.

### Table 3 Arrangement of temperature and moisture sensors at the Erlangen test site

| Number | GSHE | Borehole | Sensors | Sensor type | Installation depth | Installation depth | Installation depth | Installation depth | Installation depth |
|--------|------|----------|---------|-------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| #01    | #02  | #03      | #04     | –           | #5                | #4                | #6                | #3                | #1                |
| TR1    | TR2  | TR3      | TS2     | TS1         | Temperature sensors—inlet pipe | 0.0 m             | 0.0 m             | 0.0 m             | 0.1 m             | –                 |
| TR2    | TR3  | TS2      | TS1     | TS2         | Temperature sensors—GSHE centre | 4.0 m             | 4.1 m             | 4.0 m             | 3.9 m             | –                 |
| TS2    | TS1  | TS2      | TS2     | TS1         | Temperature sensors—GSHE centre | 6.0 m             | 6.0 m             | 6.0 m             | 6.0 m             | –                 |
| F1     | F2   | F3       | F1      | F2          | Moisture sensors—GSHE centre | 0.1 m             | 0.1 m             | 0.1 m             | 0.1 m             | –                 |
| F2     | F3   | F3       | F3      | F3          | Moisture sensors—GSHE centre | 4.0 m             | 4.0 m             | 4.0 m             | 4.0 m             | –                 |
| F3     | F2   | F3       | F3      | F3          | Moisture sensors—GSHE centre | 7.9 m             | 8.0 m             | 8.1 m             | 8.1 m             | –                 |
| TU1    | TU2  | TU3      | TU4     | TU5         | Undisturbed underground temperature (UT) | –                 | –                 | –                 | –                 | 0.0 m             |
| TU2    | TU3  | TU4      | TU5     | TU6         | Undisturbed underground temperature (UT) | –                 | –                 | –                 | –                 | 1.0 m             |
| TU3    | TU4  | TU5      | TU6     | –           | Undisturbed underground temperature (UT) | –                 | –                 | –                 | –                 | 2.0 m             |
| TU4    | TU5  | TU6      | –       | –           | Undisturbed underground temperature (UT) | –                 | –                 | –                 | –                 | 3.0 m             |
| TU5    | TU6  | –        | –       | –           | Undisturbed underground temperature (UT) | –                 | –                 | –                 | –                 | 4.0 m             |
| TU6    | –    | –        | –       | –           | Undisturbed underground temperature (UT) | –                 | –                 | –                 | –                 | 5.0 m             |

Fig. 3 Enlarged easy drill segments
Grouting

During certain test on the properties of the drilling machine producer, it was found that the procedure of grouting can influence the success of an undamaged installation of the GSHE. When removing the tubes without insertion of grouting, the GSHE can be damaged by lifting the whole spiral upwards again caused by friction between the pipes and the tube’s inner surface. If the whole drilling string would be filled with grouting before the extraction of the tube segments, a removal would not be possible caused by rubbing effects of the grains at the inner surface of the tubes. In order to ensure a successful tube extraction without damaging the GSHE, the volume (~ 0.14 m³) of the bottommost tube has to be filled carefully with grouting material to ensure a fix location within the borehole without dragging along the pipe during the reconstruction of the enlarged easy drill tubes.

The standard grouting of RAUGEo Helix was excavated material which was left from the trenching process. If underground material is too clayey, it should be removed and replaced by a more sandy material or minimum pure quartz sand to improve the thermal conductivity of the surrounding under saturated conditions (Lu et al. 2007). Pure sand is not able to retain pore/soil water as its field capacity is relatively low. On the other hand, when adding clay minerals to the mixture the ability to retain water increases and the field capacity of the backfilling material is higher (Kuntze et al. 1994). To evaluate the influence of the grouting to the performances of the new GSHEs, it was planned to test four different types of backfilling mixture at the test field in Erlangen. These mixtures were homogenized by hand using a concrete mixer. The grain size of each mixture was analysed through seaving (DIN-18123 2011), and the results are classified after the USDA soil texture diagram (United States Department of Agriculture, USDA 1987) (Fig. 4). The raw materials were washed with

![Fig. 4 Grain size distribution of backfilling mixtures and their raw materials](image_url)
building site sand (0–2 mm), clay powder out of mono-layered clay minerals and bentonite powder out of mixed-layer clay minerals. The final products (Table 4) were filled into big packs to ensure safe transportation and an accurate grouting process at the test field.

### Thermal response test as power source

To analyse the performance of a GSHE and the corresponding backfilling material within an underground system, a thermal response test (TRT) was performed on each probe in a period between July and September. During a TRT, constant heating power is initiated into the underground via circulating a heat carrier fluid for a certain volume and time through the GSHE system. The fluid temperature is measured at the inlet pipe and at the return pipe. By applying a numeric model, it is possible to maintain physical parameter (like thermal conductivity, borehole resistance) about the GSHE, the backfilling material and the underground itself. The TRT device had three power stages of 3 kW heat output each. The device had a special switch to activate only 20% of the heating power which is 600 W in this setup. As the construction depth of the new helix-type heat exchanger is 8 m, there is less pipe metre available for heat transfer compared to a standard double-U tube, for example.

The results of this ground response measurement can be obtained by applying the infinite line source model (Ingersoll and Plass 1948; Carslaw and Jaeger 1959). The analysis refers to Eq. (1) which describes the process if heat is injected into a borehole (after Gehlin 1998).

\[
T_f = \frac{Q}{4\pi \lambda H} \ln(t) + \left[ \frac{Q}{H} \left( \frac{1}{4\pi \lambda} \left( \ln \left( \frac{4a}{r_b^2} \right) - \gamma \right) - R_b \right) + T_b \right]; \quad t \geq \frac{5r_b^2}{a}
\]  

(1)

The monitoring starts at a certain time \( t \) after the application of heat injection through circulation. To simplify, Eq. (1) can be transferred to receive a linear relation between \( T_f \) and \( \ln(t) \) (Eq. 2).

\[
T_f = \kappa \ln(t) + m
\]  

(2)

With equations used in the German Standard VDI 4640/Part 5 (2016) and EN ISO 17628: 2015, important parameters can be derived for the evaluation of a thermal response test: the effective thermal conductivity (Eq. 3) and the thermal resistance (Eq. 4) between heat carrier fluid and borehole wall. For deriving the thermal conductivity, the heat output \( q \) and the inclination \( k \) of the linear relation have to be determined. For the determination of the thermal resistance of the borehole, Eq. 4 is applied where \( m \) is the intercept of the regression line \( T_f \) with \( \ln(t) \) of Eq. (2) (Witte 2012).

\[
\lambda = \frac{q}{\kappa 4\pi H}
\]  

(3)

\[
R_b = \frac{H}{Q} (m - T_b) - \frac{1}{4\pi \lambda} \left( \ln \left( \frac{4a}{r_b^2} \right) - \gamma \right)
\]  

(4)

The accuracy of a graphical evaluation approach is ± 0.05 W/(mK) for thermal conductivity and ± 0.005 km/W for the thermal resistance between borehole wall and the fluid (Gehlin 1998). For practical purposes, this accuracy is sufficient.

However, the boundary conditions for evaluating the results of a TRT cannot be analysed by using the infinite line source model. Compared to VDI 4640-Sheet 5, the installed depth is too low for this solution. As the installation depth is 8 m, seasonal/solar influences cannot be precluded. Further other models have to be deployed if the length of the GSHE is shorter than 25 m. At the Molinella test site a ground response test was carried out at a similar prototype of the new helix with different pipe dimensions. The performance of the probe’s design was already tested and evaluated using other algorithms (Zarrella et al. 2017).

Therefore, in that case, the TRT device is used to generate a constant supply of 600 W heating power over a period of at least 72 h. The response of the underground should be monitored by the installed temperature sensors.

| Table 4 Backfilling material planned to use at the Erlangen test site |
|-------------------------|----------------|----------------|----------------|----------------|
| Number | GSHE | #04 | #02 | #01 | #03 |
| Borehole | #3 | #4 | #5 | #6 |
| Mixture | 15 vol% bentonite; 85 vol% sand | 30 vol% clay powder; 70 vol% sand | 15 vol% clay powder; 85 vol% sand | 100 vol% sand |
| USDA analogue | Loamy sand | Loamy sand | Sand–loamy sand | Sand |
| Produced amount | ~ 2.1 m³ | ~ 2.1 m³ | ~ 2.1 m³ | ~ 2.1 m³ |
| Costs per tonne (without VAT and transport) | 62.70 € | 30.05 € | 22.88 € | 15.71 € |
Results and discussion

Installation

The installation of the newly developed helix was double-edged in terms of performance. The underground conditions at the test site in Erlangen were quite heterogeneous and therefore hard to penetrate. The enlarged easy drill method was conceived for unconsolidated sediments, especially for clayey soils with high plasticity. The underground in Erlangen consists of a succession of sand, weathered sandstone/siltstone and claystone layers. Within the sandy parts, there were random clay lenses which used to be quite rigid and hard to drill with this technique. In about 8 m depth there was a massive clay stone layer with interlayered formation water. As the enlarged easy drill technique is developed for clayey underground, a drilling bit similar to a chevron bit was used to abrade the material. During the drilling process, the bit was scraping into the claystone and the cuttings were mechanically mixed with the formation water at about 8 m depth. The result was a stiffy mass which was coating the borehole wall and especially the drilling tools. With this coating on the crucial parts of the drilling string, a sufficient progress was no longer assured (Fig. 5). For this reason and to secure a proper installation, following the regulations and regimentations for borehole heat exchanger installations, the technical supervisor on site determined the final installation depth to maximum 8 m which concurs with the top of the claystone layer.

Due to underground conditions, three boreholes (#3, #4, and #6) were drilled using a standard auger technique with a diameter of 390 mm. As the stability of the holes was given without attaching a casing, the new GSHEs together with the fixations for the sensors was inserted by hand. Grouting was arranged by means of a small excavator which lifts the openable big packs, filled with backfilling material, above the wellbore to refill the hollow. The remaining holes (#1, #2 and #5) were bored applying the enlarged easy drill technique or a combination together with the standard auger. The first two boreholes collapsed after removing the drilling segments as the underground and groundwater conditions were not known well and the drilling depth was not limited by the technical supervisor yet. The first attempt #1 is now used to detect the UT (sensor TU1–TU6). Borehole #5 was installed in 5 h 30 min in total. First the standard 390 mm auger was used to reach 8 m depth. During the recovery of the auger segments, the borehole collapsed from 8 m up to 2 m depth. Therefore, the drilling tool was changed and the borehole was re-drilled by utilization of the enlarged easy drill technique. As the underground was loosened, it was now easy to reach again 8 m installation depth. Due to the properties of the claystone layer and the presence of formation water, the friction at the bottom of the hole was strongly reduced. It was very difficult to unlock the drilling bit to lose. When this was finalized, the insertion of the GSHE along the smooth inner side of the enlarged easy drill segments was fast and uncomplicated (Fig. 6).

As there was no experience about the grouting process in that kind of geological setting and its consequences for pulling the casing, it was decided to rebuild the easy drill segments expecting borehole #5 will not collapse. Unluckily, the borehole collapsed during the recovery process of the segments. Now the GSHE is surrounded by a mixture of originally in situ material and topsoil instead of a mixture of 85% sand and 15% clay powder by volume. A final installation scheme of all four GSHE including the sensor’s location is displayed in Fig. 7.

Sensor’s response

The GSHEs and therefore the underground were exposed with 600 W heating power over at least three days to fulfil the general conditions for a thermal response test according to EN ISO 17628: 2015. To standardize the testing of the heat exchanging probes, values for inlet flow and return flow were taken exact 72 h after the beginning of the TRT and compared with the temperature finally arriving at the sensors (Fig. 8a, c, e, g). As time and temperature are logged at the TRT device, figures for inlet and return flow were documented and directly from there. At the same time the
undisturbed underground sensors were monitoring the environmental impact on the underground (Fig. 8b, d, f, h). It is obvious that the topmost temperature sensor TU-1 is the one most exposed to external influences as even the day–night rhythm and weather effects can be discriminated. The response of the other temperature sensors for undisturbed underground conditions is buffered from the surrounding soil and reflects long-term changes of the environmental settings. An overview about the results of the sensor's monitoring, as well as temperatures of inlet and outlet flow, is listed in Table 5.

To compare the different sensors, several boundary conditions must be complied. First of all, the underground conditions are practically identical as the distance between the boreholes is between 3 and 4 m. The sensors are adjusted at the same depth level at each GSHE in the same way. The injected heating power is constant with 600 W for 72 h. Consequently, the only varying components in the system are the backfilling mixtures and environmental conditions as the climate/weather.

GSHE #1 with in situ material was tested from August 27 until August 30, 2017. IF-1 and RF-1 are the highest compared to the remaining probes. There is a continuous decline in temperature with depth; however, the bottommost sensor TR3-1 at 8 m depth is 1.6 °C warmer than TR2-1 in 4 m depth. This complies with a heat loss at 8 m depth of 73.0% compared to inlet temperature. As the borehole collapsed from the bottom to the top during the deconstruction of the enlarged easy drill segments, it can be assumed that the backfilling material is nearly identical with the surrounding geological stratigraphy. The deeper, the more the substrate becomes clayey which would minor the thermal conductivity of the surrounding material under non-dry conditions (Bertermann and Schwarz 2017). In this case, the temperature signal could describe a heat accumulation, as the heat cannot be dissipated due to low thermal conductivity and low permeability values of the clayey material. Further, the higher clay content increases the possibility for the presence of groundwater above the impermeable layer. Therefore, groundwater effects could be the reason for the relatively high heat loss at sensors TR2-1 and TS2-1 where just 65–70% of the initial inlet flow temperature arrives.

The heat stimulation of GSHE #2, grouted with a clay powder mixture, took place from July 20 until July 23, 2017.
Fig. 8  a–h Temperature response of the installed sensors during the test period and the corresponding undisturbed underground temperature
IF-2 and RF-2 are 39.46 °C, respectively, and 37.61 °C. The shallow, undisturbed underground temperature (TU1) was the highest during all four monitoring tests (Fig. 4d). Comparing TR1-2 with TR3-2 78.8% of the heat measured at the topmost sensor reaches the sensor at the bottom sensor. This trend is even more significant if you compare the inlet flow temperature IF-2 with TR3-2 where only 63.1% reaches the sensor at 8 m depth. These are relatively the lowest values of all four GSHEs.

The heat stimulation of GSHE #3 with 100% sand as backfilling material was performed on July 17 until July 20. IF-3 and RF-3 are the lowest compared to the remaining four GSHEs with 38.76 °C inlet flow temperature and 36.90 °C of return flow temperature. The deepest sensor TR3-3 has, similar to GSHE #1, relatively high values with 29.0 °C, which is 0.8 °C colder than TR2-3 located at 4 m depth. This heat accumulation at the bottom of the GSHE could be caused by the presence of clay lenses that are prevailed in this geological setting. 74.8% of the IF-3 could be detected at the sensor TR3-3. This correlates with 88.4% of the temperature measured at TR1-3. The sensors are sorted after their installation depth as high as GSHE #1. GSHE #4 shows the similar heat accumulation as GSHE #1 and GSHE #3. The difference between TR3-4 at 8 m depth and IF-4 is 71.8% which is the second lowest value of all GSHEs. By analysing the soil body’s response, TR3-4 has 89.1% of the temperature measured at TR1-4. This reflects the highest value of all four boreholes.

### Conclusion

For comparing the four different GSHE installations regarding their performance expressed by thermal conductivity or heat extraction within the working mode, an index has to be defined. Due to the fact that several boundary conditions at the test site, e.g. geological situation, GSHE design, installation depth, heat load and injection time, can be assumed as homogeneous, the thermal performance of the used backfilling material can be derived. The performance index of the used backfilling material can be expressed by a heat transfer index (HTI). A comparison of the IF and RF temperature values does not reflect the HTI of the different backfilling materials in a holistic way. Caused by the design of the GSHE, temperature exchanging effects between the winded outer tube part and the return flow tube part which is located in the centre of the GSHE will generate mixture temperature values. For an effective comparison, the installations at the test filed and deriving the HTI the difference between IF and TR3 seem the most expedient value, whereas the temperature mixing effects are mostly limited and the results are also usable for other GSHE designs and installation methods.
Considering $\Delta T$ from IF to TR3 as HTI, sand with clay powder provides the biggest temperature decline ($14.56 \, ^{\circ}C$) of all materials (Table 5). By implication, it can be assumed that the mixture of sand with clay powder shows the best thermal conductivity at the test field. Subsequently, sand with bentonite and the in situ material, which reflects sandy loam to sandy clay loam material, provide nearly the same HTI with 10.82 $^{\circ}C$, respectively, and 11.21 $^{\circ}C$ followed by pure sand with 9.76 $^{\circ}C$.

Finally, the mixture with clay powder shows the best HTI which makes it very suitable as backfilling material for GSHEs. Further, also the price of 30.05 €/tonne of this mixture is quite affordable which result in a good cost–benefit ratio of the clay powder mixture compared to the bentonite mixture with 62.70 €/tonne. Obviously, in situ material is the cheapest solution as it is already on site and has not to be mixed in a certain composition. However, not every location provides the possibility to reuse the removed drilling material as mechanical as well as thermal properties may not be feasible enough for shallow geothermal applications. 15.71 €/tonne would be the price for 100% pure sand as backfilling material; however, the performance is about 11% worse than the clay powder mixture. Due to the enhanced water retention capacity, this solution provides more reserves in times of long-term droughts. Therefore, good alternatives have to be investigated and tested. In a next step clay powder mixtures should be tested at other types of shallow GSHEs if it provides a holistic solution as backfilling material.

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