Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Impact of Freeze-Thaw Cycles on Borehole Heat Exchangers – a Holistic Experimental Approach

Jan-Henrik Kupfernagel[1], Jan Christopher Hesse[2,3], Bastian Welsch[2,3], Markus Schedel[2,3], Lutz Müller[1], Ingo Sass[2,3]

[1]Technische Hochschule Ostwestfalen-Lippe, Geotechnical and Geothermal Engineering, An der Wilhelmshöhe 44, 37671 Höxter

[2]Technische Universität Darmstadt, Geothermal Science and Technology, Schnittspahnstr. 9, 64287 Darmstadt

[3]Technische Universität Darmstadt, Darmstadt Graduate School of Excellence Energy Science and Engineering, Otto-Berndt-Str. 3, 64287 Darmstadt, Germany

jan-henrik.kupfernagel@th-owl.de

Keywords: borehole heat exchanger, freeze-thaw cycles, hydraulic conductivity, real scale experiment

ABSTRACT

For various reasons, the inlet temperature of the heat carrier fluid in borehole heat exchangers (BHE) may fall below the freezing point of water. Consequently, temporary freezing and thawing processes occur in the grouting material and the surrounding rock formation. However, the transition zone between pipes and grout as well as the skin zone between the grout and the undisturbed subsoil are also influenced by these processes. This can lead to significant damage of the grouting material or the subsoil structure as well as cause detachment phenomena between the pipe and the grout or in the skin zone. As a result, the hydraulic integrity of the system cannot be sustained. In aquitards or aquicludes, such secondary flow paths may act as hydraulic short circuits.

Previous research on this issue focused either on the grout only or on the compound of grout and BHE-pipes, but completely omitted the subsoil as well as the skin zone. For this reason, a laboratory and a technical scale experiment were developed. The laboratory approach improves an existing measuring method, which considers a simplified geometry with just a single tube and the grout, by integrating the surrounding soil. In contrast, the large-scale experiment allows for the simulation of freeze-thaw cycles (FTC) considering a realistic BHE geometry with a double-U-Pipe embedded in a grout cylinder, which is also surrounded by compacted soil material. A sealed cylindrical steel tank with a height of 100 cm and a diameter of 50 cm encases the experiment. The device is operated like a triaxial cell. This facilitates measurements of the system's hydraulic conductivity under defined pressure conditions such as hydraulic backpressure as well as a confining pressure. The BHE pipes are connected to an external heat pump, which enables a simulation of realistic fluid temperature variations including freeze-thaw cycles. Moreover, the shell of the tank is tempered to define an outer thermal boundary condition. A radially symmetrical arrangement of temperature sensors in the cell renders a monitoring of the temperature field as well as the detection of the ice penetration depth possible.

The main objective of the experimental series is the identification of critical factors that control the integrity of a BHE systems in-situ, when numerous freeze-thaw cycles are applied.

1. INTRODUCTION

The German Federal Government aims to increase the share of renewable energies in the final energy consumption to 18 percent by 2020 and to 30 percent by 2030. More than 60 percent of the primary energy consumption are attributed to heating purposes. Therefore, it is necessary to transform not only our electricity system but also the heating and cooling sector. Geothermal energy is a renewable energy source with a high potential for replacing fossil fuels, especially in the heating and cooling sector. Most commonly, it is extracted by borehole heat exchangers (BHE), which usually tap into depths of about 70 to 200 m and deeper (DGG and DGGT 2015). BHE with depths of up to 400 m are defined as "shallow" systems, which are in the focus of this study.

1.1 Grouted Borehole Heat Exchangers

Most often, BHE in Germany are made up of two closed-loop polyethylene pipes, which are inserted into a borehole as shown in Figure 1. Subsequently, the BHE is sealed off with a cement based grout. The grouting material is thermally enhanced to improve the heat transfer. Since the natural temperatures in the shallow subsurface are too low for direct energetic use, a heat pump is necessary to achieve the required temperatures of a heating system. The heat carrier fluid that is pumped through the underground pipes is usually an antifreeze mixture of water and glycol.

The grout is of particular importance. First of all, it has to stabilize the borehole, secondly, it has to ensure an efficient heat transfer between the pipes and the natural subsurface and most importantly, it has to seal the annulus against groundwater movement. Consequently, a suitable grouting material should combine the following characteristics:

- a sufficient compression strength,
- a high thermal conductivity,
- a low hydraulic conductivity and
- its properties have to remain stable over the complete operating time and under each working condition (e.g. freeze-thaw resistance).

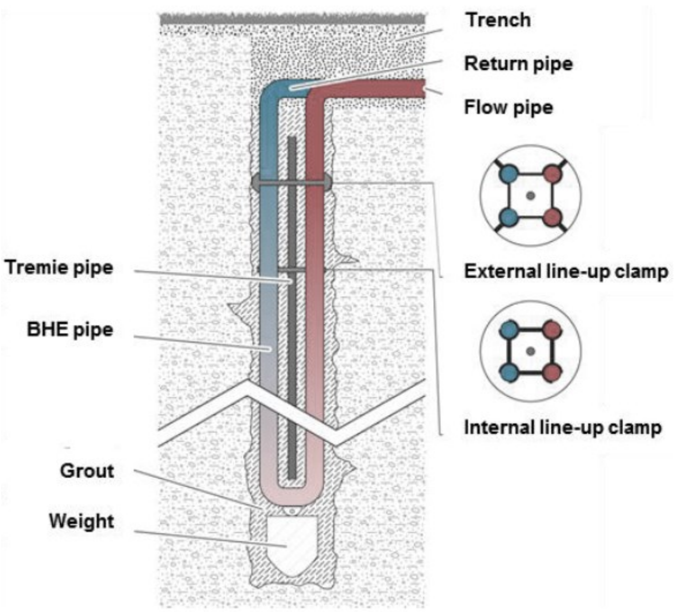

Figure 1: Sketch of a vertical BHE, Double-U-Pipe (DGG and DGGT 2015).

1.2 Increase of Hydraulic Permeability Caused by Freeze-Thaw-Cycles

During the heating period, especially during peak loads, the heat extraction by the BHE may exceed the heat influx from the surrounding rock formation (DGG and DGGT 2015). As a consequence, fluid temperatures in the BHE may drop significantly, even below 0 °C. Figure 2 shows the fluid temperature development of an exemplary BHE installed near Stuttgart (Germany) in winter 2018. Despite relatively mild outdoor temperatures during that period, the inlet flow almost continuously dropped below 0 °C for approximately four months.

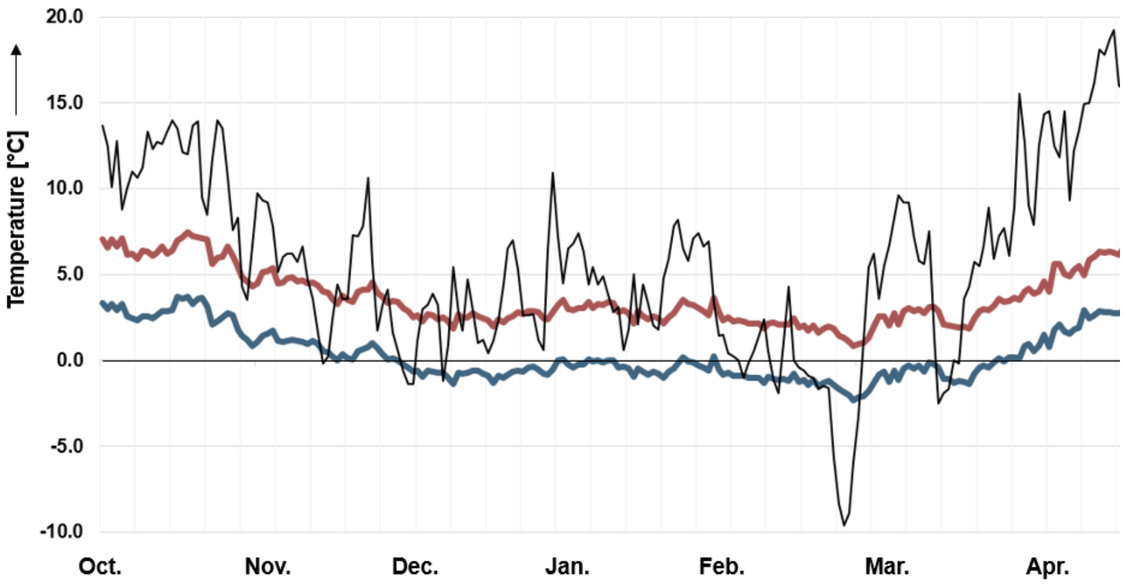

Figure 2: Mean temperatures of outlet (red) and inlet flow (blue) of an exemplary BHE near Stuttgart (Germany) during the heating season 2018 and the corresponding outdoor temperature (black).

Once, the temperature in the grouting material drops below the freezing point of the pore water, the aggregate state of the pore water changes. As a consequence, the water freezes and its volume increases. The capillary water withdraws from the capillaries and forms an ice lens through crystalline growth. This process affects the surrounding structure rather than the source of the frost front (probe pipe) itself (Unold 2006, Chamberlain and Gow 1979). If the grout and the surrounding soil are water-saturated, the mechanical pressure on the grout structure increases. As soon as the tensile strength of the material is exceeded, cracks form (see Figure 3) and lead to an increase of the grout's hydraulic conductivity (Anbergen et al. 2014). The grout in a BHE can generally be regarded as fully water saturated, particularly in sections with direct groundwater contact. However, especially these sections must be sealed by an intact grout.

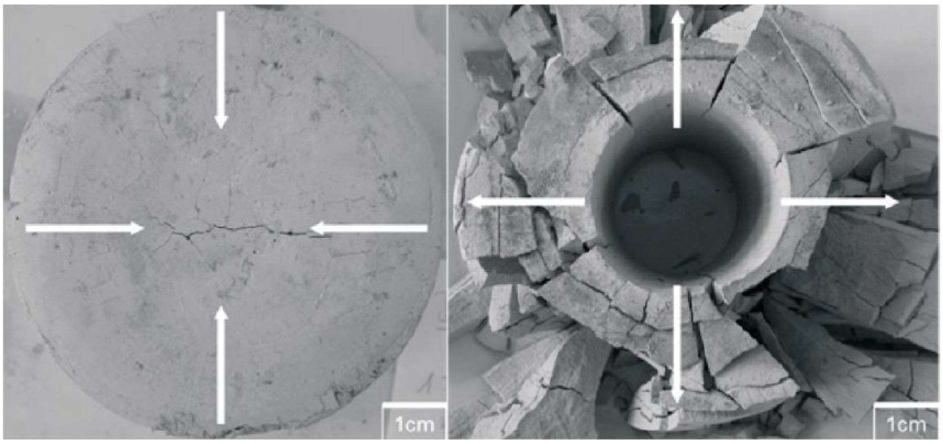

Figure 3: Comparison of the effect of the frost direction on the damage pattern. Grouting material sample (left) with frost direction from outside to inside, and (right) a system sample of grout and pipe with frost direction from inside to outside (Anbergen et al. 2014).

Previous research (e.g. Anbergen et al. 2014) on this issue focused either on the grout only (Figure 3, left) or on the compound of grout and BHE-pipes (Figure 3, right) but completely omitted the surrounding subsoil as well as the skin zone. However, with a persistent propagation of the frost front further outwards, FTC could also affect the properties of the surrounding subsoil (Dalla Santa et al. 2019). For this reason, two experimental setups are developed – one on the laboratory scale and one large-scale experiment – that extend previous approaches to a holistic system approach including pipes, the grout as well as the subsoil surrounding the BHE. Both setups will be described in the following.

2. EXPERIMANTAL SETUPS

A laboratory-scale experiment has several advantages such as reduced duration and lower technical effort. To ensure a direct comparability of our newly developed laboratory-scale experiments to the well-established measuring method by Anbergen et al. 2014, the simplified sample geometry with a single pipe embedded in a grout body is adopted. However, the transferability of its results to the real scale or to numerical models is limited, as the interaction of more than one pipes with different temperatures cannot be reproduced by such a simplified geometry. Moreover, such laboratory-scale experiments represent only a small vertical BHE segment. Consequently, the experiment does not allow profound conclusions concerning e.g. the vertical crack propagation. For these reasons, a large-scale test is built, which reproduces a real horizontal cross-section of a double U-pipe BHE.

2.1 Laboratory-Scale Experiment

The experimental setup (see Figure 4) combines the three system components heat exchanger pipe, grouting material and soil in a test cell to assess the effects of FTCs on the hydraulic conductivity. It allows for measurements according to ASTM D-5084 (2010), including a radial confining cell pressure. The heat exchanger pipe, which has a diameter of 40 mm, is situated in the center of the setup. It is surrounded by a hollow cylinder-shaped grout body with an outer diameter of 100 mm, which in turn is embedded in a soil body with a diameter of 140 mm. The total height of the specimen adds up to 200 mm.

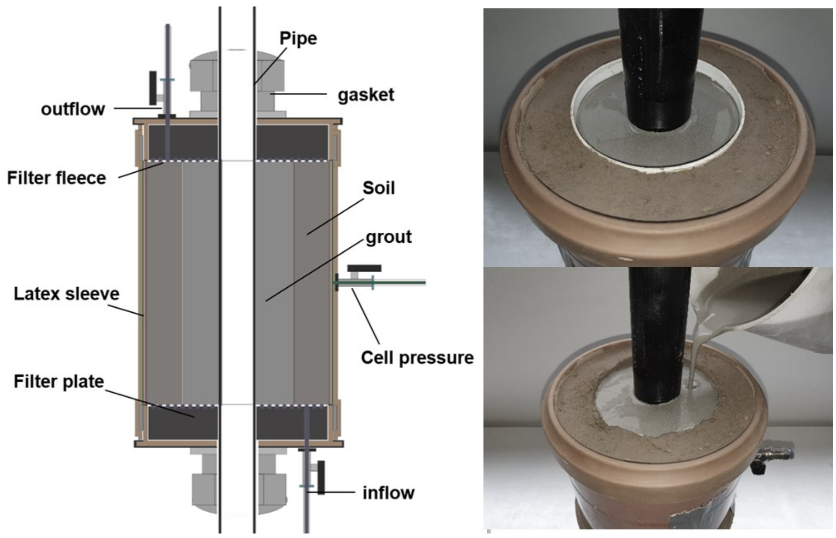

Figure 4: Schematic sketch of the laboratory-scale experiment for system investigations and determination of the system hydraulic conductivity of pipe, grout and soil under consideration of FTCs (left). Open cell with built-in soil and centered pipe (top right). In-between is a white spacer tube, which is filled with grout and then pulled (bottom right).

The outer shell as well as the top and bottom plates of the cell are made of PVC. In addition, drainage layers and a filter fleece are installed in the top and bottom plate to allow for uniform flow through the sample and to avoid suffusion. The heat exchanger tube is clamped in the middle of the cell. A white spacer tube (Figure 4, top right) is used to separate the grouting material and the soil during the installation. The soil is installed with optimal water content and proctor density outside the spacer tube. The grouting material is mixed according to the manufacturer's instructions and filled into the space between the heat exchanger pipe and the tube. Subsequently, the spacer tube is pulled out and the cell is closed.

After a curing time of 56 days, the specimen in the cell is saturated with deaerated water. Afterwards, the baseline measurement of the hydraulic conductivity is conducted (flow direction from bottom to top). As in previous experiments (e.g. Anbergen at al. 2014), the sample is frosted from the inside to the outside until the temperature on the outside of the specimen drops below 0 °C. In total, six FTCs are performed. After each cycle, a hydraulic conductivity measurement is carried out. In the end, all measurements are compared to the baseline value to quantify the effect of the FTCs. Moreover, a comparison to the system test including only pipe and grout body without surrounding soil facilitates a validation of the results as well as a quantification of the effects, which must be attributed to the surrounding soil.

2.2 Large-Scale Experiment

The large-scale experiment (see Figure 5) is installed in a sealed cylindrical steel tank with a height of 100 cm and a diameter of 50 cm, which represents a large-scale triaxial cell. Its internal structure is comparable to that in the lab experiment. However, instead of a single pipe, four pipes are installed in the grout body, whereby a real double U-pipe BHE geometry can be realized in the horizontal cross-section.

The outer shell of the tank is connected to a heat pump and can be tempered. This allows for a complete control over the temperature field in the tank and thus the simulation of e.g. a realistic temperature drawdown in the near-field of the BHE. A latex membrane is installed between the tank shell and the specimen body to reproduce the earth pressure and to prevent sidewall leakage. The BHE pipes are placed inside a spacer tube. The installation of the soil and grout is accomplished in the same manner as described in chapter 2.1: the soil is filled in with optimal water content and compacted, the grouting material is poured in right before the spacer pipe is pulled out.

To monitor the temperature development within the specimen body, several temperature sensors are installed in the middle horizontal plane of the tank (Figure 6). They are placed radial symmetrically in the soil and at the skin zone between soil and grout. Moreover, the temperature of the inflow and outflow of the BHE pipes is monitored as well as the temperature of the tank shell. Consequently, the thermal boundary conditions are known at any time of the experiment. This facilitates the reproduction of the experiment in numerical simulations.

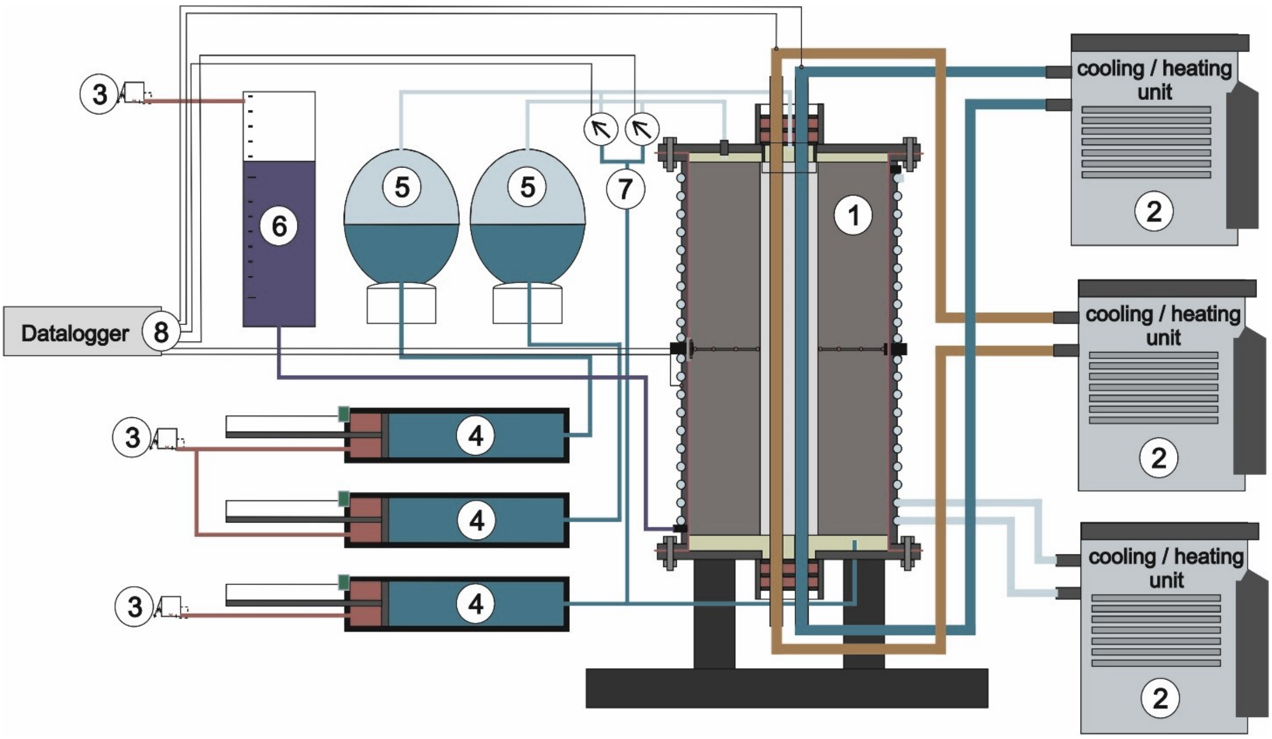

Figure 5: Schematic sketch of the large-scale test. (1) Tank with external temperature control, soil filling and built-in BHE. (2) Pre- and return temperature control of the BHE. (3) Pneumatic control, (4) Volume pressure control measurement of the hydraulic conductivity with (5) separation of flow path between BHE and soil. (6) Cell pressure and measurement of displacement, (7) Differential pressure measurement and (8) Data logger

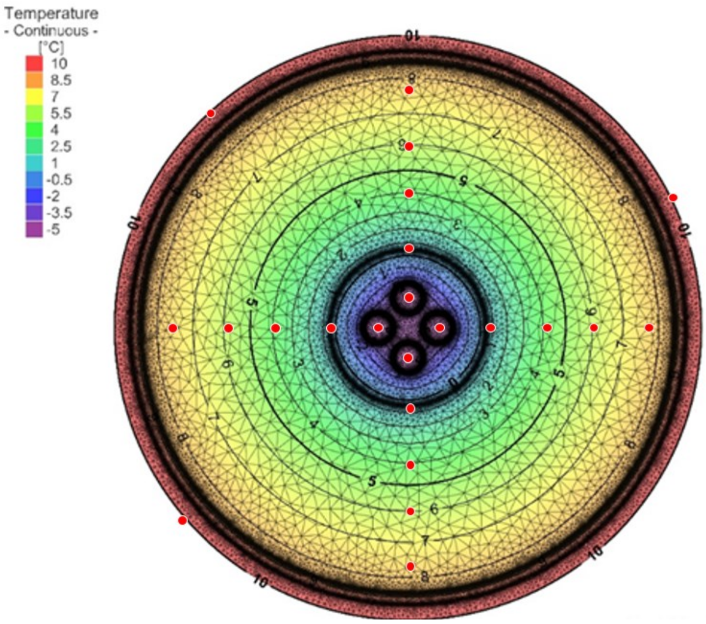

Figure 6: Numerical simulation of the cross section of the large-scale experiment with exemplary temperatures of -5°C inside the probe and 10°C on the tempered tank shell and position markings for the temperature sensors (red).

Hydraulic conductivity measurements of the test specimen can be carried out using the backpressure method based on ASTM D-5084 (2010). Just as in the laboratory experiment, the water flows through the sample from the bottom to the top and the inflow is distributed over the entire cross-section. The return flow is discharged at two separate points: one sampling point drains water, which has flowed through the soil, the other one samples water, which has flowed along the contact surfaces of the pipes and through the grout body. This allows for an allocation of permeability changes caused by FTC to the grout zone and to the soil zone. The return flow is separated from the measuring unit by a full membrane vessel. Pneumatic cylinders with a high-resolution of the piston displacement carry out the measurement itself.

As the setup as well as the experiment itself is complex, one test execution will take several months. During this time, the BHE is subjected to realistic load cycles. The temperature-dependent stress is gradually increased until the frost front penetrates the soil to some extent. This allows for an investigation of the influence of FTC on the hydraulic conductivity of the grout, the skin zone and the soil.

3 CONCLUSION AND OUTLOOK

Freezing and thawing processes can occur in the subsurface near BHE systems during their operation. Depending on the composition and condition of the subsoil and the grout, even ice lens formation may occur. Especially fine-grained soil and grouting materials are prone to this effect, which can have negative impacts on the hydraulic properties of the grout as well as the surrounding soil.

In our study, the influences of FTCs are investigated and quantified using laboratory and large-scale experiments. The approach allows for qualitative statements about the damage effects as well as a quantitative assessment of the impairment of the hydraulic conductivity of the overall system pipes – grout – soil. The experiments are still running at the time of submission. Consequently, no experimental data is available yet. However, the experiments proceed according to plan and the results will be presented on the World Geothermal Congress 2020.

One major task will be the upscaling of the experimental results to real BHE dimensions. However, in situ data, which could be used is scarce, since it is expensive and almost impossible to integrate depth-resolved temperature monitoring into existing BHEs. BHE constructions, in which such a monitoring, for example in the form of fiber-optic temperature measurements, is realized, are mostly large-scale applications or heavily subsidized showcases with a generous design. Data obtained there cannot be regarded as representative for prevalent BHE applications (i.e. heating of single-family homes). For this reason, the experimental investigations conducted here are accompanied by numerical simulation studies. One of these studies investigates the frost formation in and near BHE installations with a fully discretized finite element BHE model assuming realistic operating conditions and integrating freezing and thawing behaviour (Welsch et al. 2020). Nevertheless, results from experimental investigations such as described here, are imperative for the correct implementation of freezing and thawing processes in such numerical simulation tools and, consequently, for increasing their validity.

ACKNOWLEDGMENT

The publication originates from the research project OPTIMOG (project no.: 03ET1472A/B), which is financially supported by the German Federal Ministry for Economic Affairs and Energy.

Supported by:

Federal Ministry
for Economic Affairs
and Energy

on the basis of a decision
by the German Bundestag

REFERENCES

Anbergen, H., Frank, J., Müller, L., Sass, I.: Freeze-Thaw-Cycles on Borehole Heat Exchanger Grouts: Impact on the Hydraulic Properties, *Geotechnical Testing Journal,* **37**, (2014), 639-651.

ASTM Standard D-5084. Standard test methods for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter. Annual book of ASTM Standards, ASTM International, West Conshohocken, Pa., USA (2010).

Chamberlain, E.J. and Gow, A.J., 1979. Effect of freezing and thawing on the permeability and structure of soils. *Engineering Geology*. **13**: (1979) 73–92.

Dalla Santa, G., Farina, Z., Anbergen, H., Rühaak, W. and Galgaro, A.: Relevance of computing freeze-thaw effects for borehole heat exchanger modelling: A comparative case study, *Geothermics* **79,** (2019), 164-175

DGG and DGGT: Empfehlungen des Arbeitskreises Geothermie – Oberflächennahe Geothermie – Planung, Bau, Betrieb, Qualitätssicherung, Deutsche Gesellschaft für Geowissenschaft e.V. (DGG) und Deutsche Gesellschaft für Geotechnik e.V. (DGGT) (Ed.), Ernst & Sohn, Berlin, Germany (2014).

Floss, R.: Technische Zusätzliche Vertragsbedingungen und Richtlinien für Erdarbeiten im Straßenbau ZTVE-StB 94, ED 1997, Kommentare mit Kompendium Erd- und Felsbau, Kirschbaum Verlag Bonn, Germany (1997)

Unold, F.: Der Gefriersog bei der Bodenfrostung und das Kompressionsverhalten des wiederaufgetauten Bodens, Dissertation an der Universität der Bundeswehr München, (2006).

Welsch, B; Hesse, J.C.; Kupfernagel, J-H.; Schedel, M.; Müller, L.; Sass, I.: Penetration Depth of Freeze-Thaw Processes in Borehole Heat Exchangers, Proceedings World Geothermal Congress 2020, Reykjavik, Iceland, April 26 – May 2, 2020