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

THM Experiments for the Investigation of Freeze-Thaw Processes Around Borehole Heat Exchanger Systems

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

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

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

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

hesse@geo.tu-darmstadt.de

Keywords: Shallow Geothermal Systems, Borehole Heat Exchangers, Freeze-Thaw-Processes, Thermo-Hydraulic-Mechanic Coupling (THM) and Unfrozen Water Content

ABSTRACT

Freeze-thaw processes induced in the immediate environment of borehole heat exchangers (BHE) as a result of operating temperatures below 0 °C can significantly damage the compound structure consisting of the BHE pipes, the cement based grout as well as the surrounding subsoil. The hydraulic integrity of such systems is not ensured anymore and its thermal efficiency could be significantly impaired. However, detailed knowledge on freezing and thawing processes in porous media, such as the grout and unconsolidated rock materials, is still incomplete. It is known, that the content of unfrozen water has a strong impact on material properties influencing the overall heat and mass transfer processes. Moreover, freezing strongly depends on various boundary conditions such as the soil type or pore water chemistry. Accordingly, it is essential to have adequate information about the freezing interval for different boundary conditions, which describe the transition from pure liquid water to the ice phase and vice versa. Therefore, a thermo-hydraulic-mechanical (THM) experiment is used to gain a more detailed knowledge of the freezing processes in BHE grouts and unconsolidated rock materials. For this purpose, an ultrasonic measurement device is linked to the freeze-thaw experiment: The wave velocity in solid particles in the observed temperature range is constant and not affected by temperature changes. However, with descending temperature, the ice content increases, which leads to an improved cross-linking of the solid soil particles. As a consequence, the bulk P-wave velocity increases with decreasing unfrozen water content. Hence, this relationship can be used to determine the content of unfrozen water during a freeze-thaw cycle. In addition to ultrasonic measurements, the growth of ice lenses and the resulting mechanical deformation of the system are monitored. The results of the THM experiments should be afterwards implemented in numerical models, which allows an upscaling of the experimental findings to the field scale.

1. INTRODUCTION

The use of BHE in combination with heat pumps for heating of buildings represents a successful and sustainable technology. However, the installation and operation of BHE requires a high degree of diligence in order to avoid a conflict of use with drinking water extraction. A usually concrete-based grouting material, which is installed in the annulus between the BHE and the borehole wall, should seal the BHE-system and thus guarantee the integrity of the whole structure. The integrity of the system can be expressed by its bulk permeability. During the heating period, BHE are often operated at fluid temperatures in the freezing zone to gain higher efficiencies. This freeze operation leads to thermal loads in the BHE-system, which can result in secondary flow paths in the form of cracks in the grouting material or detachment of the grouting material from the pipes. This has been confirmed for various grouting materials by Müller (2009) and Anbergen et al. (2014). They found out that the direction of freezing – in case of a BHE-system from inside to outside – has a strong influence on the resulting damage pattern. Moreover, they showed that the material permeability can differ significantly from the system permeability (combined specimen of pipe and grouting material). Before this, just the grouting material had to fulfill a maximum permeability criterion to ensure the sealing of a BHE-system. Since these findings, in Germany the system permeability is the decisive parameter, as it comprises also possible detachments between the pipes and the grouting material. A widely used method for measuring the system permeability has been developed by Anbergen et al. 2014.

The recently released reprint of the German regulation VDI 4640-2 (2019) specifies that after six freeze-thaw cycles in such a device, the system hydraulic conductivity of the pipe-grout-specimen may only be increased by one order of magnitude compared to the value of the unfrozen system sample. In addition, the grouting material itself must equal or undercut a hydraulic conductivity coefficient k_f of $1 \cdot 10^{-10}$ $m \cdot s^{-1}$. A task group from different German authorities has recommended that the vertical hydraulic conductivity of a BHE-system should at no time and at no depth exceed the natural vertical hydraulic conductivity of the surrounding subsoil. A strict, universal limit is not considered necessary (SGD 2015). If there is no value for the initial hydraulic conductivity, the system hydraulic conductivity should not be greater than $\leq 1 \cdot 10^{-9}$ $m \cdot s^{-1}$.

Another consequence is that some German authorities do not allow fluid temperatures in the BHE-system below -3 °C anymore and presuppose the use of so-called frost monitors so that freeze-thaw processes are completely avoided in BHE-systems (LQS EWS 2018). However, such a strict temperature limit can lead to a significant loss of system efficiency.

Another approach could be the application of BHE materials, which are resistant to freeze-thaw cycles and able to maintain the integrity of the BHE system as a whole over many years of operation and with a larger number of freeze-thaw cycles or significant fluctuations in fluid temperature. However, the development of such materials lags behind, as the basic knowledge on freeze-thaw-processes in porous media is still fragmentary.

In porous media, like grouting materials or soils, water does not freeze suddenly, but over a certain temperature range. Even at temperatures well below 0 °C, water can be present in the liquid phase. The temperature range of the transition from liquid water to ice is called freezing interval. In the case of a uniform cooling, the first ice crystals form in larger pore spaces, from which they continue to grow. Depending on the temperature and pressure state of the soil body, a residual part of the water remains in the liquid phase - also depending on the type of soil, the organic content and the pore water chemistry (Banin and Anderson 1974). This is particularly the case in cohesive and clayey soils, since the surface charges of the individual particles are significantly higher and thus more water molecules are adsorbed on the particle surface than with non-cohesive soils. The adsorbed water, so called bound water, has a higher density and higher viscosity as the free water in the pore space. It has also a lower free enthalpy than free water, which leads to lower freezing temperatures (Fripiat et al. 1984). The portion of liquid residual water is referred to as the unfrozen water content. It has a strong influence on the material properties of porous media and influences the heat and mass transport processes (Li et al. 2016). Another aspect in cohesive, water-saturated, low permeable soils is the formation of ice lenses. There is a broad consensus that the thickness of the ice lenses depends on the temperature gradient, the water permeability of the soil and the level of suction tension. The criteria that are responsible for the beginning and end of ice lens growth and thus for the distance between the ice lenses are still unclear (Unold 2006). Anbergen et al. 2014 observed that ice-lenses in a cylindrical freeze-thaw grouting sample are larger at higher radii.

Because of all these aspects it is necessary to determine the freezing interval and the associated parameters as accurately as possible under various boundary conditions. For this purpose, a test setup was developed, which allows for the determination of the thermo-hydraulic-mechanical (THM) processes associated with ice formation in the subsurface.

2 EXPERIMENTAL SETUP

The experimental setup consists of a modified triaxial test system. It is used for cylindrical soil and grouting samples with a diameter up to 100 mm and a height of up to 200 mm (see Figure 1). The confining pressure liquid (water-glycol-mixture) can be tempered via a secondary cooling circuit (copper coil around the sample) down to -25 °C. This creates a temperature boundary condition on the outer surface of the sample body that allows for the sample to be frozen from the outside to the inside in a controlled manner. The temperature is measured with a Pt-100 sensor at the latex membrane, which envelopes the lateral surface of the sample in order to distribute the confining pressure uniformly on the sample and also avoid flow paths along the sample surface during the permeability testing. Furthermore, the confining pressure is gained by a plunger system, which can generate pressures up to 16 bar. Mechanical parameters such as the freezing pressure are recorded by an axial load sensor and a displacement sensor. In addition, the radial deformation can be observed by the volume displacement of the confining liquid. Moreover, the hydraulic conductivity of the sample is determined according to DIN 18130-1 (1998). The fluid temperatures during the flow-through experiment can be varied between 5 °C and 25 °C to represent natural groundwater temperatures. Besides that, the triaxial cell is equipped with an ultrasonic measuring system, which is employed to determine the freezing interval.

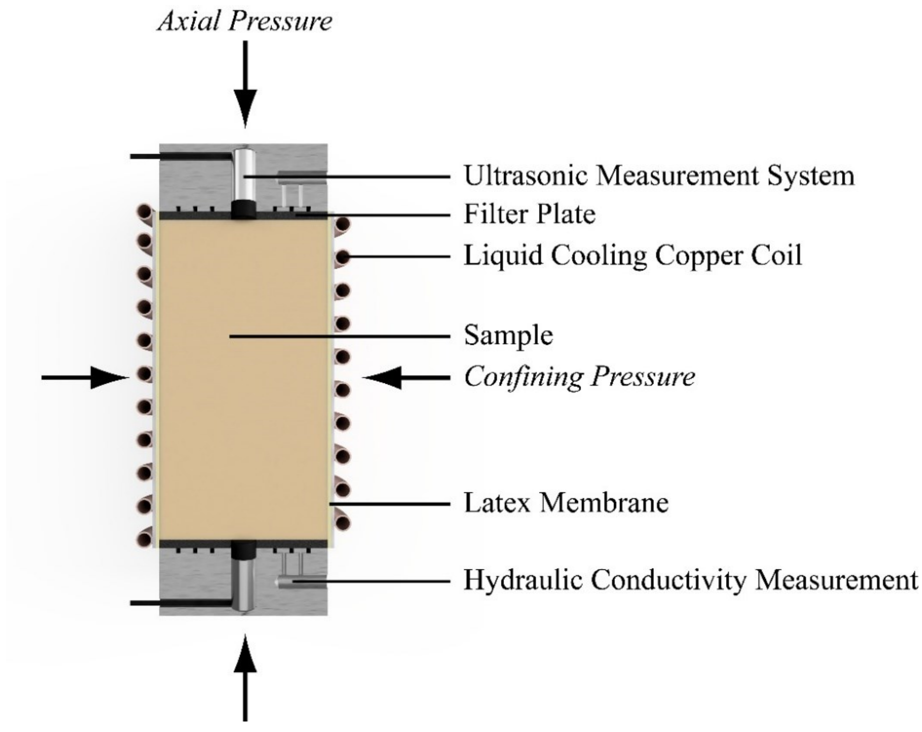

Figure 1: Sketch of the triaxial cell for the THM Experiment, soil sample with a 100 mm diameter and 200 mm height.

2.1 Ultrasonic measurements to determine the unfrozen water content

The wave velocity in solids can be assumed to be constant over the temperature range relevant for BHE (Wang et al. 2006). However, as temperatures fall below 0 °C, the ice content in the pore space of the sample increases. Since ice has almost twice the P-wave velocity of liquid water, the effective P-wave velocity in the sample rises significantly with decreasing content of unfrozen water. This correlation is used to determine the proportion of unfrozen water by means of ultrasonic measurements (Li et al. 2016). It is necessary to use an amplifier in the measurement setup due to the attenuation of the ultrasonic wave by the water in the pore space, which is particularly pronounced close to the freezing interval.

2.2 Preliminary experiments

In a preliminary test, this ultrasonic effect could already be reproduced on a loam soil and a silt loam soil (see Figure 2) with the specifications given in Table 1.

Table 1: Soil properties.

	Loam	Silt Loam
Optimal Water Content w_{pr} in Mass-%	14.5	14.1
Proctor density 100 % in $g \cdot cm^{-3}$	1.87	1.80
Organic Content in Mass-%	2.7	1.7
Grain density ρ_s in $g \cdot cm^{-3}$	2.75	2.71

The loam and silt loam were compacted in the laboratory under Proctor water content and afterwards samples were taken with an 80 mm core cutter. Then the samples were saturated with degassed, deionized water. Subsequently, the saturated samples were frozen for 24 hours at a certain temperature and then immediately connected to an ultrasonic system (see Figure 3) with a measuring frequency of 80 kHz. Each sample was just used for one temperature step to avoid damages of the sample from previous freezing. At each sample, five P-wave velocities were measured and averaged.

After the ultrasonic measurement, the saturated hydraulic conductivity was determined – once before and once after freezing to -10 °C. The measurements were conducted using the KSAT-device from METER Group, which works according to the principle of Darcy`s Law.

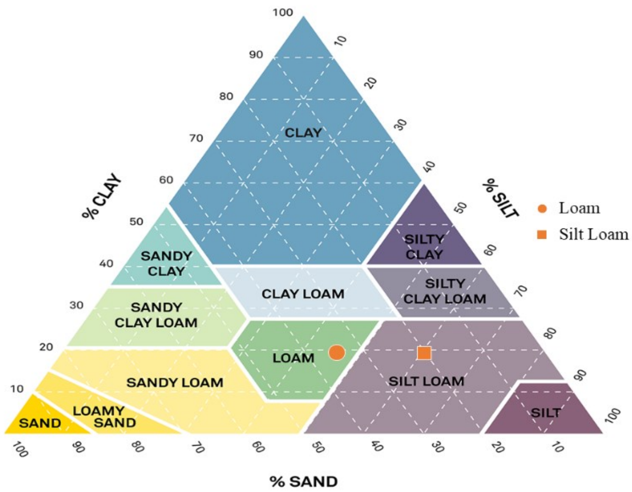

Figure 2: Classification of the two soils according to the USDA soil taxonomy.

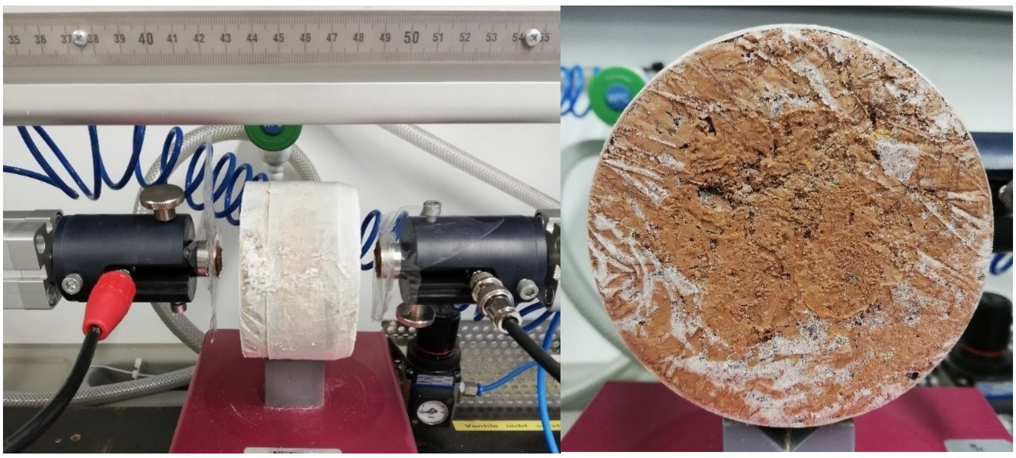

Figure 3: Left: Preliminary setup with an ultrasonic measurement system (UKS-D with UGS 40). Right: Frozen loam sample in a 80 mm core cutter after the measurement.

3 FIRST RESULTS

The results (Figure 4) reveal an increase of the P-wave velocity of the two soils with decreasing temperatures. However, the increase of P-wave velocity also attenuates with decreasing temperatures. The pore space is more and more covered by ice instead of water, so that a reduction in temperature leads only to minor changes in the P-wave velocity.

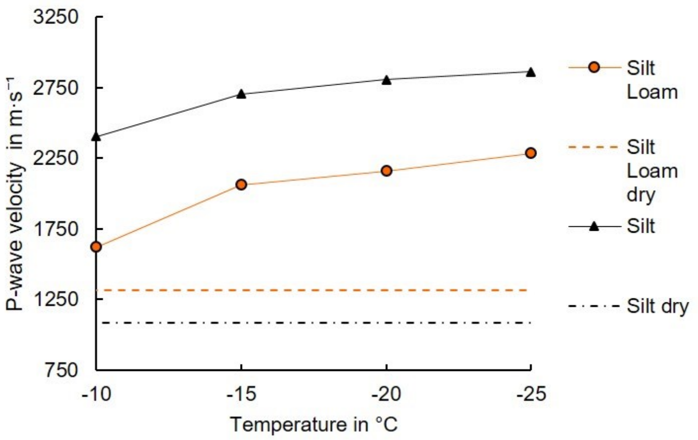

Figure 4: Results of the preliminary ultrasonic measurement for the two kinds of soil, n=3.

The results of the saturated hydraulic conductivity measurements are shown in Table 2. It is obvious that the loam has a lower hydraulic conductivity before freezing than the silt loam. After freezing to -10 °C and thawing again the saturated hydraulic conductivity of the loam increased by more than one order of magnitude. For the silt loam, there is also an increase observable, but it is far smaller than that for the loam. For a comparison also sand sample was measured. However, it showed more or less no freezing induced changes of the saturated hydraulic conductivity.

Table 2: Saturated hydraulic conductivity.

	K_s before the freezing in $m \cdot s^{-1}$	K_s after freezing to -10 °C in $m \cdot s^{-1}$
Loam	$2.11 \cdot 10^{-9}$	$2.95 \cdot 10^{-8}$
Silt Loam	$1.88 \cdot 10^{-8}$	$1.11 \cdot 10^{-7}$
Sand	$6.01 \cdot 10^{-5}$	$6.86 \cdot 10^{-5}$

4. CONCLUSIONS AND OUTLOOK

The results of the preliminary experiments indicate that the soil type around BHE has a large influence on the ice growing processes. One of the critical parameters is the content of unfrozen water, which was neglected in previous research. Therefore, it is important to consider the soil as part of the BHE system with all the necessary parameters. The processes associated with ice formation in the subsurface must be regarded as THM-coupled. With the help of the new measuring setup, all important parameters could be determined in one experiment. This will contribute to a better understanding of freezing and thawing processes in porous media in general, which can then be applied to the BHE-system.

Moreover, the results of the ongoing THM-experiments will be used to develop and validate suitable THM coupled numerical models. These models should enable for the upscaling to real installation conditions in the field. Furthermore, the results shall be used to optimize grouting materials and the BHE pipes, which are resistant to freezing and thawing and facilitate the preservation of the system’s integrity and efficiency over many years of operation.

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.

Banin, A. and Anderson, D. M.: Effects of salt concentration changes during freezing on the unfrozen water content of porous material*, Water Resources Research*, **124-6**, (1974).

DIN 18130-1: Baugrund, Untersuchung von Bodenproben - Bestimmung des Wasserdurchlässigkeitsbeiwerts - Teil 1: Laborversuche, Deutsches Institut für Normung e.V., Beuth-Verlag, Berlin, (1998).

Fripiat, J.J., Letellier, M. and Levitz, P.: Interaction of water with clay surfaces, Philosophical Transactions of the Royal Society of London, A311, (1984), 287-299.

Li, D., Huang, X., Ming, F. and Zhang, Y.: The Impact of Unfrozen Water Content on Ultrasonic Wave Velocity in Frozen Soils, *Procedia Engineering*, **143**, (2016), 1210-1217.

Müller, L: Frost-Tau-Wechselbeständigkeit von Hinterfüllbaustoffen für Erdwärmesonden*, Bbr Fachmagazin für Brunnen- und Leitungsbau*, **07/08;** wvgw Wirtschafts- und Verlagsgesellschaft Gas und Wasser mbH, Bonn, (2009).

Staatliche Geologische Dienste (SGD): Empfehlungen für die Anforderungen an die hydraulische Durchlässigkeit des Systems Erdwärmesonde, Ad-hoc-Arbeitsgemeinschaft Hydrogeologie, erarbeitet für den Bund/Länder-Ausschuss Bodenforschung (BLA-GEO) durch die Staatlichen Geologischen Dienste der Deutschen Bundesländer (SGD), (2015).

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

VDI 4640-2: Thermische Nutzung des Untergrundes – Erdgekoppelte Wärmepumpenanlagen, Verein Deutscher Ingenieure e.V., Beuth-Verlag, Berlin, 2019

Wang, D., Zhu. Y., Ma, W., Niu, Y.: Application of ultrasonic technology for physical-mechanical properties of frozen soils*, Cold Regions Science and Technology*, **4**, (2006), 12-19.