Modelling Thermo-Hydraulic Coupled Phase Change Processes of BHE Induced Ground Freezing

Dalla Santa Giorgia[1], Galgaro Antonio[1,2], Farina Zeno[1], Di Sipio Eloisa[3], Anbergen Hauke [4], Rühaak Wolfram[5,6]

[1] Department of Geoscience, University of Padua, via Gradenigo, 6, I-35131 Padova, Italy

[2] CNR – IGG, Institute of Geosciences and Earth Resources, via Gradenigo, 6, I-35131 Padova, Italy

[3]GeoCentre of Northern Bavaria, Friedrich-Alexander-Universität Erlangen- Nürnberg, Schlossgarten 5 91054 Erlangen, Germany

[4] APS Antriebs-, Prüf- und Steuertechnik GmbH – Wille Geotechnik, D-37124 Rosdorf, Germany

[5] Technische Universität Darmstadt Institute of Applied Geosciences, Department of Geothermal Science and Technology, D- 64287 Darmstadt, Germany

[6] Technische Universität Darmstadt Graduate School of Excellence Energy Science and Engineering, 64287 Darmstadt, Germany

giorgia.dallasanta@studenti.unipd.it; giorgia_dallasanta@yahoo.it

ruehaak@geo.tu-darmstadt.de

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ABSTRACT

The heat exchange with the subsoil related to a ground source heat pump closed-loop borehole heat exchanger (BHE) system has been shown to alter the natural thermal status of the surrounding sediments (Banks, 2012). When it is necessary to improve the rate of heat extraction per meter from the underground, anti-freezing solutions are added to the carrier fluid, in order to lower its working temperature. In such cases, the induced thermal anomaly is more intense and can cause freeze-thaw cycles (FTCs) in the surrounding sediments.

FTCs in cohesive sediments affect irreversibly the soil structure, resulting in a change of sediments' mechanical and hydraulic properties. Hence, it is important to estimate correctly the maximum propagation of the frost front induced by a BHE system, in order to evaluate the volume involved in the critical thermal processes. This work presents a modelling evaluation of the BHE thermal impact on the underground, considering the case of induced FTCs. A newly developed plug-in is applied to FEFLOW finite element modelling. The plug-in, not only incorporates the sediments' thermal properties in frozen state, but also considers the phase change of the pore water by taking into account the release of latent heat.

In this case the plug-in is applied to a fully discretized model representing a transversal section of a double-U BHE working with a high percentage glycol fluid. A real case scenario is considered where the loads are considerably unbalanced towards heating. The propagation of the thermal plume is simulated with and without application of the plug-in; finally the results are compared.

1. INTRODUCTION

In closed-loop Ground Source Heat Pump (GSHP) systems, the heat exchange with the underground is provided by a heat-carrier fluid flowing inside the boreholes. Especially in cold regions, a water-glycol mixture is usually used in order to provide a sufficient temperature difference between heat-carrier-fluid and surrounding soil. Hence, it is possible to run the BHE with working fluid temperatures below 0°C. If the BHE is used mainly for heating, it is likely that the soils temperature will decrease next to the borehole, especially at the end of heating periods (Rybach and Eugster, 2010; Zanchini et al., 2012). If the system is designed unbalanced, the temperature in the surroundings will continuously lower by time. Furthermore, also in case of undersized boreholes or in case of an increase in the heating energy demand, a lowering of the working temperature inside the BHE can considerably increase the heat extraction from the ground.

With working temperatures below 0°C, the temperature in the vicinity of the BHE can drop below the sediments' freezing temperature inducing FTCs (Eslami-nejad and Bernier, 2012). If cohesive

sediments experience FTCs, the micro-structure is irreversibly affected (Chamberlain and Gow, 1979; Konrad, 1989; Coussy, 2005), resulting in a change of their geotechnical properties (Othman and Benson, 1993; Esch, 2004; Qi et al., 2006; Qi et al., 2008). The effects in the nearfield of BHEs hasn´t been investigated sufficiently so far. Only some first contributions have been recently published with respect to the induced settlements in the normal-consolidated cohesive sediments in dependence from the overburden pressure (Dalla Santa et al., 2016a) or in dependence from the pore water salinity (Dalla Santa et al., 2016b). However, in all the cases FTCs are potentially caused in the subsoil, it is important to estimate correctly the propagation of the temperature profile (Haehnlein et al., 2013).

The presented research combines experimental measurements of sediments' thermal conductivity in frozen state with thermo-hydraulic coupled modelling. The finite element code FEFLOW (Diersch, 2014) is applied and modified by a phase-change plug-in (Anbergen et al., 2014). Since the sediments' thermal properties are also modified when in frozen conditions, the frozen/unfrozen state of the soil needs to be taken into account. For this purpose, several experiments were performed on silty clay at different temperatures. The exact thermal conductivity and heat capacity in both frozen and unfrozen conditions were obtained. Moreover, also the freezing intervals of the studied sediment are estimated at several states of compaction.

In addition, the developed plug-in takes into account not only the variation of the sediments' thermal properties in frozen and unfrozen conditions, but also the release of the latent heat during the phase change.

In this paper a study case of a double-U BHE with prevalent heating demand and high rate of heat extraction is considered. The plug-in is applied to a fully discretized model representing a transversal section of the BHE and the surrounding sediments. Two BHE sections of a depth of 4 m and 20 m are represented.

The aim of this work is to show how the thermal plume caused by an unbalanced geothermal system varies if latent heat effects are considered or not. It is shown that the use of the plug-in results in a significantly different propagation of the thermal plume. As the heat transport respects the thermodynamic effects of the phase change, it is assumed that the results are more realistic. The results are useful in case of progressive lowering of the subsoil temperature due to buildings' unbalanced thermal requests, as in all other cases of sub-zero working temperatures.

2. THERMO-MECHANIC EXPERIMENTS

The experimental measurements performed aim firstly to define the thermal parameters in frozen and unfrozen conditions. Secondly, the freezing interval of the tested sediment are quantified, by measuring the temperature at which the freezing process starts and the one at which the freezing process is mainly concluded (Bing and Ma, 2011). The sediment tested is a silty-clay collected in the Venice area. In table 1 the main physical features are listed.

Table 1: Main features of the tested sediment.

		atterberg limits				mineralogical composition [%]					grain composition [%]		
soil	unified soil classification system	liquid limit	plasticity index	organic content [%]	specific gravity	*phyllosilicates*	*quartz*	*calcite*	*dolomite*	*feldspaars*	*>0.06*	*>0.01*	*>0.002*
SJ1	CL	35	14	2	2.791	31	13	22	29	5	95	62	20

2.1 Definition of the thermal parameters in frozen and unfrozen conditions

The sediments' thermal properties depend on several factors such as mineralogical composition, organic content, water content, soil density and overburden pressure (Abu-Hamdeh, 2003). The thermal conductivity and diffusivity of a given sediment changes according to the temperature variations (Nikolaev, et al., 2013; Tarnawski et al., 2009). In frozen condition, the partial filling of the voids with the ice enhances the conductive heat transport as ice has a thermal conductivity about four times higher than water. In coarse soil, the thermal conductivity may be considered to increase abruptly as the sediment freezes; while in fine-grained soils the increase is more gradual (Farouki, 1981).

The experimental measures of the thermal parameters were performed by means of the ISOMET2114, a portable hand-held measuring device. It follows a transient heat transfer method (linear source method) to assess the thermal properties of a material. Measurement is based on analysis of the temperature response of the tested material to heat flow impulses. The heat flow is excited by electrical heating of the resistor inserted into the probe, which is in direct contact with the specimen. The evaluation of thermal conductivity and volumetric heat capacity is based on periodically sampled temperature records as function of time, provided that heat propagation occurs in an semi-infinite medium (Luo et al., 2016). The instrument measures directly the thermal conductivity λ and thermal diffusivity, this way an indirect

measurement of the volumetric heat capacity is possible.

The material was prepared in order to have two samples, hosted into two cans, with an initial water content of 70%. Two cycles of measurements were achieved for every can considering different step temperatures, maintaining the sample at constant temperature for each step for at least 24 hours before collecting the measure. As for the phase changes, the samples were maintained at the sub-zero temperature for at least 72 hours. The temperature control was obtained by a climate chamber that allows imposing the desired values. The temperatures considered were: +20; +2; -8; -20; +40 °C, respectively. Therefore, the values of the thermal parameters in frozen and unfrozen conditions were obtained. The volume and the weight of the samples were measured at every temperature step in order to check the variations in water content and density.

2.2 Definition of the freezing process

The freezing point of the pore water in cohesive sediments is some degrees below 0°C, depending on the kind of sediment (mineralogical composition and granulometry), water content, salt content and state of compaction (Konrad, 1989; Marion, 1995; Bing and Ma, 2011). In addition, the phase change of the pore water occurs gradually into the voids and micro-porosity inside the sediment structure (Konrad and Morgenstern, 1980). During the freezing process at a given temperature, a part of water freezes, whereas a certain fraction remains liquid and the process proceeds gradually. Hence, also the freezing interval, defined by the temperature interval in which the phase change mainly occurs, depends on the sediment features and on its state of compaction and water content (Konrad, 1989; Farouki, 1981; Bing and Ma, 2011).

Another series of measures were performed on the same testing sediment in order to find out its freezing point (referred to as critical temperature ***Tcr***) and interval, as it is necessary to define the freezing process in the FEM modelling plug-in (Anbergen et al, 2014). The tests were conducted in a special device consisting in a thermally controlled oedometer. Two oedometer tests were carried out subjecting the sediment to a constant vertical load and a 24-hour cyclic temperature variation (from -5°C up to +55°C), applied at the end of the consolidation process due to the applied load at room temperature, as diffusely described in Dalla Santa et al. (2016a). The two similar tests were performed by applying a constant load equal to 40 kPa and 200 kPa, in order to represent the state of compaction related to the layers of sediment lying at the depth of 4 m and 20 m, respectively.

In addition to the vertical deformation of the sample, the inner temperature was continuously measured with a probe inserted into the stone base under the sample. From the comparison of the two measured temporal series, the sediment's freezing interval can be defined. The freezing point (***Tcr***) is identified in correspondence to the beginning of the expansion phase as well as the depletion of the variation in volume fixes the temperature at which the freezing process is completed.

3. FINITE ELEMENT MODEL

The first model performed represents a single BHE of 80 m length. The ground properties (thermal conductivity, density and specific heat capacity) are inferred from the experimental measures performed in laboratory on the silty clay samples. The values assumed in the modelling are listed in table 2. The undisturbed ground temperature is assumed equal to 13°C, whereas the heat flux from below is assumed equal to 0.03 W m^{-2}. The model is assumed saturated but without groundwater flow, to simulate a soil that has all pore spaces filled with water.

Table2: The main values assumed in the FEM modelling.

BHE:		
BHE depth	80	m
Borehole diameter D	0.14	m
pipe distance w	0.07	m
pipe outside diameter	0.032	m
pipe wall thickness	0.003	m
pipe inside diameter	0.026	m
Thermal conductivity pipe	0.42	W/mK
Thermal conductivity grout	1.5	W/mK
CARRIER FLUID: water+glycol (25%)		
Density	1033	kg/m3
dynamic viscosity at bulk temperature	0.0079	kg/m s
Thermal conductivity	0.475	W/mK
Specific heat	3930	J/kg K
Volumetric heat capacity	405.969	MJ/m3 K
MATERIAL PROPERTIES		
Hydraulic conductivity	9.00E-10	m/s
Porosity	0.487	
Thermal conductivity (bulk)	1.3	W/mK
Volumetric heat capacity (bulk)	2.16	MJ/m3 K

The thermal profile is characterized by a prevalent heating demand and high rates of heat extraction (figure 1).

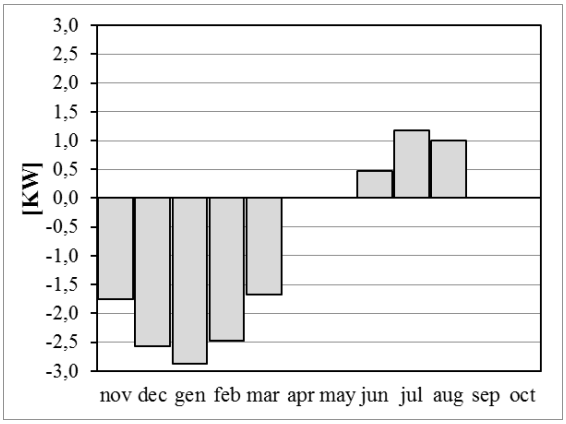


Figure 1: The applied thermal profile.

3.1 The fully discretized model

Output information from the full BHE model is taken as input for the fully discretized model. The difference between the two models is that, in the first, the BHE is simulated in its entirety as a 1D nodal sink/source boundary condition for heat transport, where a pre-defined extraction or injection of thermal energy is applied to a selection of nodes. In a fully discretized model however, the BHE is "built" with the mesh. This kind of model allows verifying in detail the propagation of heat and thermal plume inside the tubes, grout and soil in close-proximity to the BHE.

The mesh of the fully discretized model is depicted in figure 2, inserted in a complete domain of 20 m x 20 m x 0.5 m. It represents a cylindrical slice of the total-length-BHE model (taken as 50 cm thick) at two depths -4 m and -20 m from ground level.

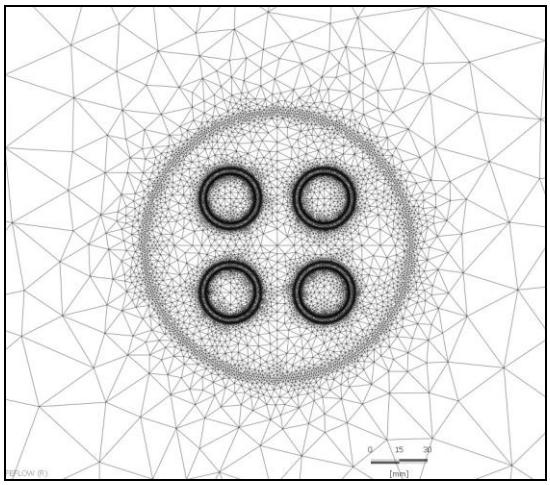


Figure 2: Fully discretized BHE model, where the BHE is modelled as part of the mesh.

The total-length-BHE model previously run provides the initial and boundary temperature conditions for the fully discretized model:

- subsoil undisturbed temperature at the considered depths
- heat-carrier fluid flowrate
- heat-carrier fluid temperature.

In this way, it is possible to simulate with great accuracy how temperature varies inside and in close proximity to the BHE.

3.2 The freezing-thawing plug-in

In order to simulate the phase change of the pore water with its relevant influence on the thermo-hydraulic coupled processes, a FEFLOW plug-in was applied. FEFLOW is commonly used as finite element software that simulates coupled heat and mass transfer in porous media (Diersch, 2014).

The plug-in respects the thermal effects on the propagation of the temperature plume using the apparent heat capacity method (e.g. Mottaghy and Rath 2006). As water in porous media does not change its phase instantaneously but gradually over a temperature range, a freezing interval is defined. Within this freezing interval the crystallization process happens and consequently the crystallization energy (latent heat) is released. In order to take the crystallization process thermally into account, the heat capacity is increased during the phase change. The solution was benchmarked with a diversity of other FEM codes in order to prove the accuracy and performance of the phase-change plug-in (Rühaak et al., 2015).

The measured data from this experimental study were directly implemented into the plug-in and the exact freezing-interval, the thermal conductivity and heat capacity were respected in the calculations.

Besides the calculations for the conductive heat transport, the plug-in modifies the hydraulic coupled convective heat flow as well. The hydraulic conductivity decreases as ice reduces the effective water pore area.

For the comparison of the influence of phase-change processes during the operation of BHEs, the model was run with or without the developed plug-in.

4. RESULTS AND DISCUSSION

4.1 Thermal parameters and freezing interval

Figure 3 shows the experimental values of the thermal conductivity (figure 3a) and thermal diffusivity (figure 3b) obtained from the experimental measures performed. Every value is the average of 3 measurements automatically repeated by the instrument.

The device used is equipped with two types of measurement probes. The needle probe, usually adopted for unconsolidated sediments, was applied to measure the thermal properties of the sediment in the unfrozen state, while the plain probe, usually adopted for solid rock samples, was used for the measurements conducted on the silty-clay in frozen state.

The measurements performed in frozen conditions showed numerous difficulties and had to be repeated several times. The problem was that the plane-source

probe needs a smooth and flat surface of the sample to obtain precise results, while the freezing process led to the growth of iced strings on the surface of the silty-clay sample and caused roughness of the surface. Hence, a first series of results is shown here which have to be confirmed with additional measurements. Nevertheless, the experimental results supply reasonable values which can be used to define the thermal parameters for the model.

The obtained values highlight the significant increase of the thermal conductivity in frozen conditions, when the iced filling of the voids become dominant in the heat transfer process. At the same time, the volumetric heat capacity decreases substantially.

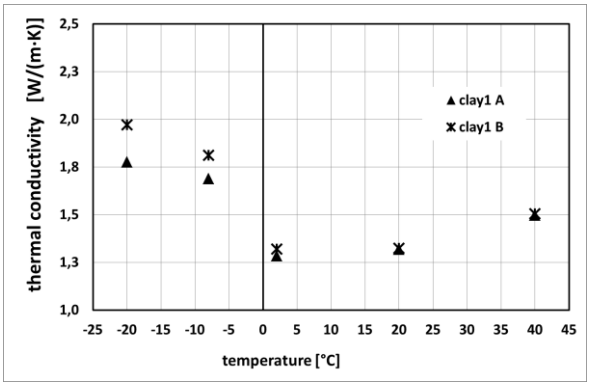


Figure 3a: Thermal conductivities obtained from the experiments at defined temperature levels.

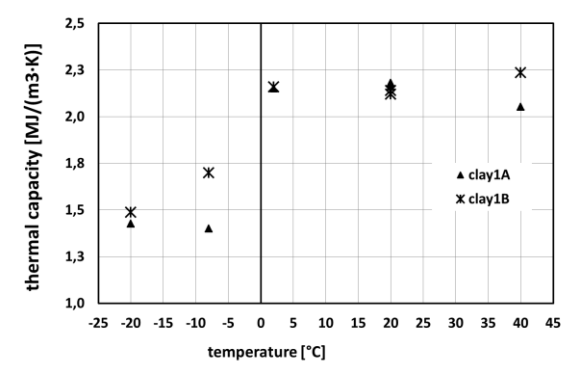


Figure 3b: Volumetric heat capacities obtained from the experiments at defined temperature levels.

The values to be used in the model are related to the measured ones, the thermal conductivity is defined equal to 1.32 W m^{-1} K^{-1} for T > Tcr and to 1.81 W m^{-1} K^{-1} in frozen condition (for T < Tcr), while the volumetric heat capacity is defined equal to 2.16 MJ m^{-3} K^{-1} for T > Tcr and to 1.7 MJ m^{-3} K^{-1} in frozen condition.

The freezing point of the sediment and the freezing interval to be used in the fully discretized model originate from the measurements performed during the oedometer tests (Table 3; see Dalla Santa et al., 2016a), in dependence to the state of compaction achieved with the applied vertical load (40 kPa or 200 kPa) combined with the imposed FTC.

Table 3:The main values assumed in the discretized FEM model.

	depth of the represented layer [m]	
values assigned in the fully discretized model	**- 4**	**- 20**
porosity	0.495	0.438
hydraulic conductivity (m/s)	8.72E-10	3.00E-10
definition of the freezing interval:		
starting temperature ***Tcr***	-2	-2.5
temperature at which the sample is mainly frozen ***T****	-4	-4

4.2 Modelling results

Figure 4 and 5 depict the results gained from the fully discretized modelling of two BHE sections (corresponding at the depth of 4 m and 20 m, respectively). On the left side the thermal anomalies obtained applying the plug-in on the fully discretized model is shown, while on the right size the thermal plumes obtained without using the plug-in is shown.

The results obtained by using the plug-in show a more extent and intense thermal plume than the one without this plug-in. In table 4 the distance from the BHE wall at which the isotherm 0°C and -2°C (identified as the freezing point) are noted, in case the plug-in was applied to the modelling or not, respectively.

Table 4: Comparison between the distance from the BHE wall of the most significant isotherms provided by the modelling by using the original plug-in or not.

	depth of slice represented[m]			
	-4		**-20**	
distance from BHE wall [cm]	**isotherm 0°C**	**isotherm -2°C**	**isotherm 0°C**	**isotherm -2°C**
with plugin	21.0	7.5	17.0	5.5
without plugin	13.5	5.5	11.5	4.5

5. CONCLUSIONS

In GSHP systems, lowering of the BHE carrier fluid working temperature in order to improve the rate of heat extraction can induce FT cycles in the sediment close to the BHE. It's known that cyclic FT processes affect significantly the cohesive sediments' mechanical properties. Therefore it is important to enhance the methods capable to estimate the evolution of the extent of the thermal anomaly in the ground.

The modelling of the induced FT processes requires a comprehensive approach and appropriate numerical solving procedures, suitable to reproduce the complex coupling of thermo-hydro-mechanical problems in

multi-phase porous materials in the presence of liquid-to-solid phase changes.

Herein the original FEFLOW plug-in (Anbergen et al, 2014) is applied to two cylindrical sections of a BHE working with anti-freezing additives.

The experimental measurements of thermal conductivity and volumetric heat capacity performed in frozen and unfrozen conditions were used as thermal model parameters. Moreover, some oedometer tests supply the freezing intervals of the considered silty-clay.

The model results show that the use of this particular plug-in supplies a more precise evaluation of the induced thermal plume.

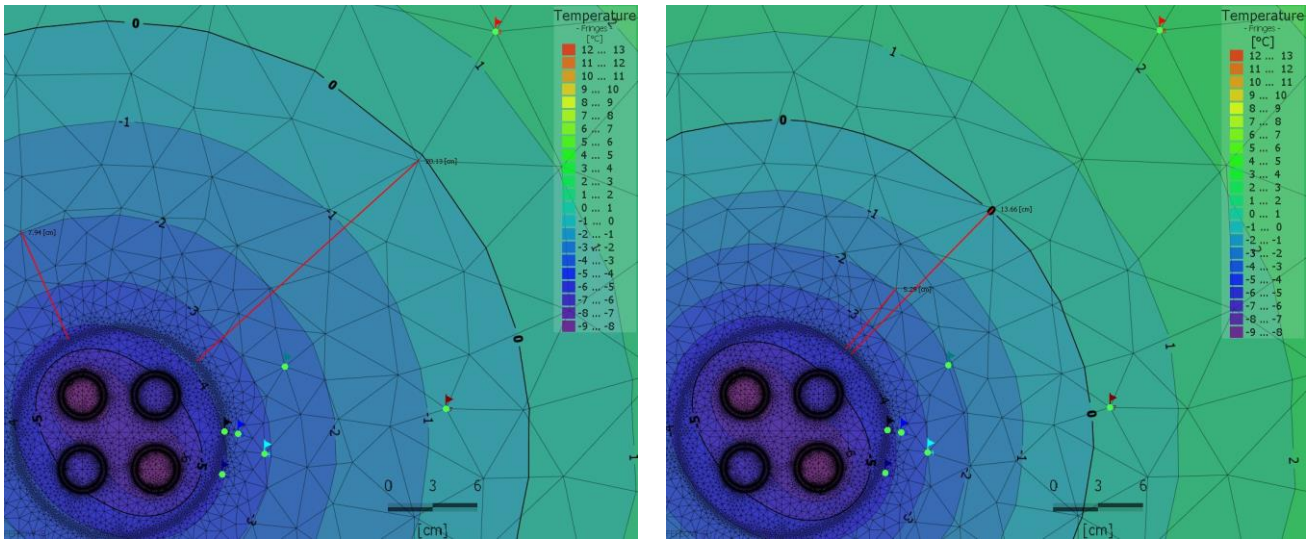


Figure 4: The thermal anomaly estimated by means of the FEM model (developed with FEFLOW) in correspondence to the BHE section at the depth of 4m. On the left side the isotherm distribution obtained by using the original plug-in is shown, in comparison with the ones obtained without the use of the plug-in, which are reported on the right side.

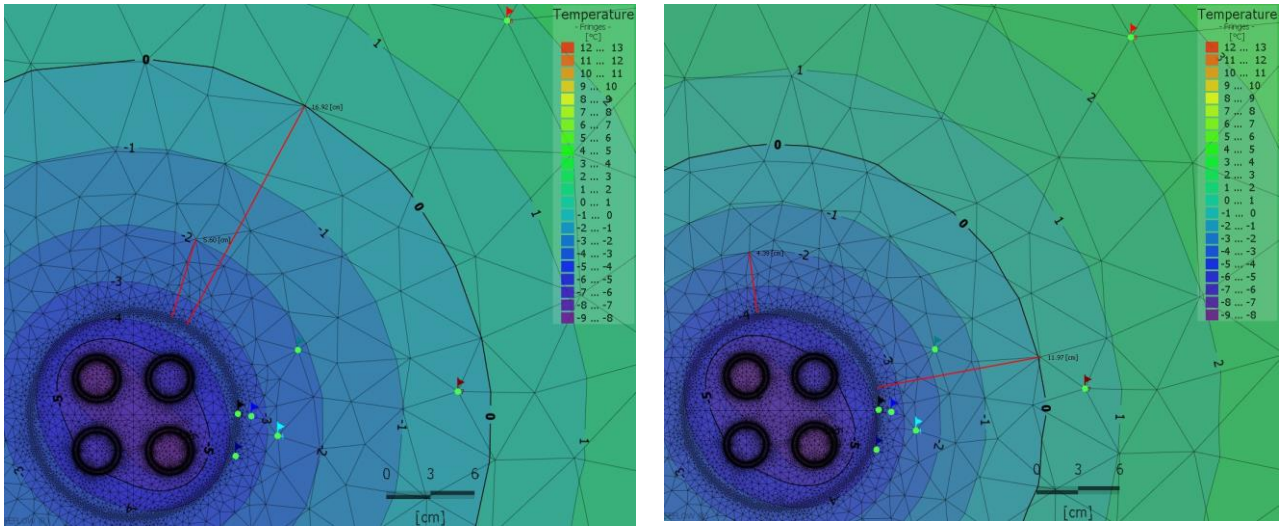


Figure 5: The thermal anomaly estimated by means of the FEM model (developed with FEFLOW) in correspondence to the BHE section at the depth of 20m. On the left is shown the isotherm distribution obtained by using the original plug-in developed, in comparison with the ones obtained without the use of the plug-in, which are reported on the right side.

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