

Environmental hazards due to extreme thermal stress induced by borehole heat exchangers

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ABSTRACT

In Ground Source Heat Pump systems (GSHP), a continuous circulation of a fluid inside the Borehole Heat Exchangers (BHE) transfers heat between the ground and the building's conditioning system. Therefore, the natural thermal status of the subsoil in the boreholes' surrounding is altered. The international community has already pointed out the importance of restricting the thermal anomalies induced in the soil, through the establishment of a minimum temperature threshold for the brines inside the probes. As a matter of fact, the heat carrier fluids often consist of mixtures of water and anti-freezing additives, which permit to decrease the temperature of the exchanger also below the water freezing point.

This paper presents a first summary of how the cyclic thermal stress induced by a heat exchanger could change some physical and geotechnical properties of soils, in case the fluid is carried at sub-zero temperatures, therefore inducing cyclic freezing-thawing and heating processes in the ground. The effects of these processes are also demonstrated with the results of a wide laboratory investigation performed on some cohesive soils.

1. INTRODUCTION

In GSHP systems the thermal exchange with the underground is provided by a heat-carrier fluid that flows into the BHE.

This fluid extracts heat from the underground during winter, while in summer the heat is removed from the building and released into the ground. The heat exchange processes affect the natural temperature of the subsoil close the probe. In order to improve the heat extraction from the ground during winter, anti-freezing solutions (generally glycol) are often added to the heat carrier fluid, so it can lower its working temperature down to -5°C or even more, in

dependence on the percentage of glycol and on the kind of heat pump utilized. Obviously, the fluid working temperature and its discharge in the BHEs are continuously modified by the heat pump in order to provide the building's heat requests, in relation on the local climate conditions and the thermal exchange capacity of the ground-probes system (Luo et al., 2016).

The use of brines with anti-freezing additives and working temperature below 0°C are usually used in case of very cold climate, characterized by low ground temperatures and unbalanced building's thermal loads towards heating. Nevertheless, also in temperate climate regions this practise is quite common because it allows designing GSHP systems with reduced probes' total length, lowering the installation costs. Moreover, the glycol can be added subsequently during the long-term use, with the aim to increase the thermal gradient between the ground and the BHEs if, with time, the soil temperature next to the boreholes has been intensely lowered, due to a no-equilibrated use of the system (Rybach and Eugster, 2010; Zanchini et al., 2012). Furthermore, the augment of heat withdrawal from the ground in winter time could be necessary also in order to provide a possible increase in building's heating request not considered during the design phase of the system.

The thermal exchange between GSHP and the ground obviously alters the natural thermal status of the surrounding subsoil. If the heat carrier fluid works at very low temperatures, the induced thermal anomaly is more intense and extent. In some cases, it could induce temperatures lower than the sediments' freezing point in the BHE proximity. Hence, it can induce not only heating process (up to +35°C or more in some cases) but also freezing and thawing (FT) cycles in the sediments close to the probe (Banks, 2012; Zanchini et al., 2012; Eslami-nejad and Bernier, 2012). Both of these thermal stresses can modify cohesive sediments' properties, but the FT processes are demonstrated to have the higher impact.

The freezing point of sediments is some degrees below 0°C, and varies depending on the kind of sediment, water content, salt content and imposed load (Bing and Ma, 2011; Marion, 1995). While coarse materials display very low sensitivity to temperature variations, the presence of clayey fractions makes the deposits particularly affected by thermo-mechanical modifications related to phase changes of the interstitial fluids (Konrad, 1989; Meunier, 2005).

Despite in literature it is known that FT processes affect irreversibly the physical and mechanical properties of cohesive sediments, as summarized by Qi et al. (2006 and 2008), the application of this knowledge to closed loop geothermal systems is missing. Moreover, in some cases, the FT cycles could modify also the internal structure of the grout used to seal off the BHE's internal tubes (Anbergen et al., 2014). Some kinds of grouts show the formation of radial and vertical fractures caused by FT processes, with a consequent deterioration of their capability to seal off the borehole and of the thermal exchange capacity of the whole system.

Therefore, it is clear that a sub-zero working temperature in the heat carrier fluids has to be used carefully. Nevertheless, in the geothermal community is not given yet sufficient consideration to this issue and its consequences, despite the necessity of limit the thermal anomalies by the BHE systems has already been pointed out (Haehnlein et al., 2013).

Herein, at first the development and the effects of FT cycles on clayey sediments are summed up. After this, the main results of a wide laboratory program aimed to investigate the effects of FT processes on some silty-clays subjected to the same conditions existing in the layers surrounding a BHE are summarized (the relative tests are diffusely described in Dalla Santa et al., 2016a and 2016b). The mineralogical and grain-compositions of tested materials are typical of sediments widely diffused in low-plain areas. The imposed temperature variations are comparable to those induced by a BHE connected to solar panels for the summer recharge, hence that works at sub-zero temperatures in winter and high temperatures in summer. The performed experiments investigated mainly the thermally induced mono-dimensional deformation under various vertical loads and interstitial water salinities. In addition, the possible modifications in vertical permeability are briefly discussed.

2. FREEZING-THAWING PROCESSES IN CLAYEY SEDIMENTS

In clayey sediments, the electrical interaction between the pore fluids and the negative charges on the particle surfaces forms the so-called electric double layer.

As the ground temperature falls below the sediment's freezing point, in the centre-most part of the pores the ice lenses begin to form from the phase change of the free water molecules. If the phase change progresses,

these crystallization centres attract other water molecules, starting from the less connected to the double electrical layer (Chamberlain and Gow, 1979; Konrad and Morgenstern, 1980). On the same time, the ice growing induces the displacement of the surrounding particles that tend to group together in some very compacted nucleus. As the temperature rises again, the ice melting gives a sudden abundance of free water that, due to the action of the vertical load, in drained conditions can squeeze out from the porous media with the consequent occurrence of a macroscale soil compaction and an immediate thaw settlement (Konrad, 1989; Esch, 2004). The whole process results in an irreversible rearrangement of the soil particles, leading to larger and dryer solid aggregates with enlarged and more interconnected pores (Chamberlain and Gow, 1979; Coussy, 2005; Farouki, 1981).

The first FT cycle has the greatest influence on the texture and the modifications in physical and mechanical properties mainly occur in relation to the first FT process that the sediment experiences (Konrad, 1989; Qi et al., 2008; Othman et al., 1994). In cyclic conditions, the changes diminish cycle after cycle; after the 5th-7th cycle, a new state of equilibrium is achieved and the structure no longer experiences further modifications (Konrad, 1989; Esch, 2004; Qi et al., 2008).

3. EFFECTS OF FREEZING-THAWING CYCLES ON PROPERTIES OF COHESIVE SEDIMENTS

A quite general and comprehensive summary of effects of FT cycles on the properties of cohesive sediments is presented by Qi et al. (2008) and Othman et al. (1994). As regards the cohesive deposits located near a BHE, the more significant effects appear to be the thermally induced consolidation and the possible changes in vertical permeability.

3.1 Thermally induced consolidation

As for the consolidation effect, several studies show that FT cycles lead to a compaction of loose deposits, although in overconsolidated samples the opposite occurs (Viklander, 1998; Qi et al., 2008).

To analyse this aspect, several thermal mono-dimensional compression were carried out on natural silty clays collected in the Venice area, North Italy (Table 1 lists the main characteristics of the tested soils). The experiments were conducted in a thermally controlled oedometer, where the sample was subjected to a constant vertical load and to a daily variation in temperature between -5°C and +55°C. The preparation procedure, the expressly made laboratory device used and the resulting deformation measured in the samples are described in detail in Dalla Santa et al. (2016a). The induced settlement was measured considering several conditions of thermal and mechanical loading, considering sediments with different IP and pore water salinity.

Table 1: Main characteristics of the tested soils.

soil code	unified soil classification system	atterberg limits		organic content [%]	specific gravity	mineralogical composition [%]					grain composition [%]			kind of experiment performed
		liquid limit	plasticity index			phyllo-silicates	quartz	calcite	dolomite	feldspars	>0.06 [mm]	>0.01 [mm]	>0.002 [mm]	
SJ1	CL	35	14	2	2.791	31	13	22	29	5	95	62	20	influence of overburden pressure
SAS	CH	59	36	2	2.750	45 (13 smectite)	39	3	0	13	93	70	35	influence of mineralogical composition
SJ2	CL	39	16	2.1	2.762	30	11	42	15	2	95	80	33	influence of pore water salinity

The thermally induced consolidation was initially investigated in normal-consolidated (NC) samples in order to study the effect of FT cycles in relation with the overburden stress. In order to achieve the correspondent state of consolidation, the oedometer samples is loaded for about 72 hours at constant temperature. Later, maintaining constant the vertical load, the temperature was varied in order to measure the strain induced by the FT cycles. The results are summarized in table 2 (extracted from Dalla Santa et al., 2016a).

The results on soil referred as **SJ1** (see table1) show that the thermally induced deformation is equal to 9.3% under an applied load of 40kPa. The higher the applied load, the lower the irreversible thermally induced deformation. Nevertheless, a significant thermal consolidation occurs also under high loads (200, 500 and 800kPa).

It is worth noting that the consolidation effect appears to be intensified in more active clayey sediments characterized by higher plasticity indexes (Liu et al., 2011). Cohesive sediments consisting of not trivial presence of smectite minerals are more sensitive to temperature changes resulting in a more water dependent behaviour (Jefferson, and Rogers, 1998). The experiments performed on cohesive material with higher IP (referred to as **SAS1** in table1) show that, as expected, the thermally induced deformation is more significant as reported in table 2.

Table 2: The thermally induced consolidation depending on the applied mechanical load in NC samples comparing the experimental results obtained testing the soils SJ1 and SAS1.

Vertical load applied [kPa]	Primary consolidation effect [%]	Thermally induced deformation [%]	Primary consolidation effect [%]	Thermally induced deformation [%]
	SJ1		SAS1	
40	3.6	9.0	3.1	16.3
200	7.3	5.5	14.3	13.6
500	14.3	4.0	-	-
800	18.0	3.5	-	-

If we consider completely saturated conditions and an average soil density of about 20kN/m³, the applied loads can represent the in-situ overburden effective

stresses at increasing depth along the probe. Figure 1 shows how, despite the higher effects occur in the shallower layers, if FT cycles are induced in the BHE proximity, consolidation processes establish in clayey layers all along the probe. Moreover, it highlights that in case of high IP the cohesive layer will display higher effects.

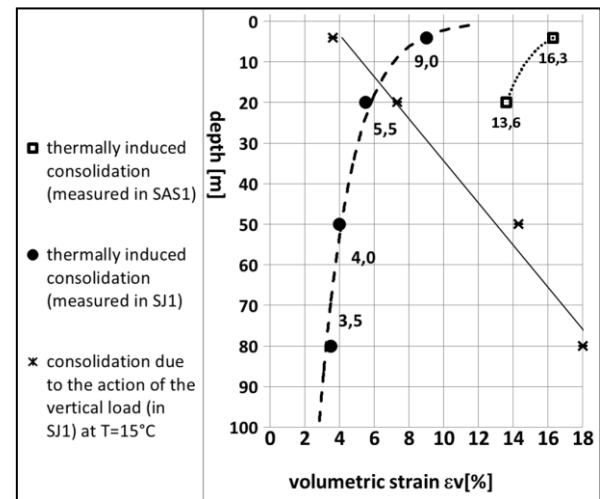


Figure 1: The thermally induced consolidation gained from the measurements performed on SJ1 and SAS1, in comparison.

Afterword, the influence of salinity of the interstitial fluids on the thermally induced deformation was studied. The results are reported in table 3, extracted from Dalla Santa et al. (2016b). In this case, the same experimental procedure previously described was applied to specimens reconstructed with a solution containing 0, 35, 70 and 140g/l of NaCl, respectively. The tested soil is referred as **SJ2** (see table 1). The vertical stress applied in these experiments was fixed equal to 40kPa and therefore the load-induced strain was almost the same for all the specimens. Therefore, only the thermally induced deformation dependence on the pore salt content was here reported (Table 3).

The tests show that the presence of salt in the pores increases the thermally induced compression, all other factors being constant. On the other hand, the presence of salts in the interstitial fluid lowers the temperature at which the freezing process begins, therefore providing a sort of protection to sediments against freezing. Moreover, due to the effect of exclusion of salt from ice formation, in cyclic FT conditions the

soil freezing temperature decreases at every cycle (Dalla Santa et al., 2016b).

Table 3: The thermally induced consolidation measured at several interstitial salt contents in NC samples (extracted from Dalla Santa et al. (2016b)).

Salt content of the added solution in the slurry preparation [g/l]	Thermally induced deformation [%]	Starting freezing temperature at the first cycle [°C]
0	7.3	-2.1
35	8.4	-2.8
70	9.1	-3.5
140	7.0	-4.6

In case of over-consolidated deposits, as expected from literature, the consolidation effect decreases increasing the over-consolidation ratio OCR. Up to OCR=15 the deformation is still a compaction, while at higher OCR, the soil exhibits a very low expansion, as reported in Figure 2.

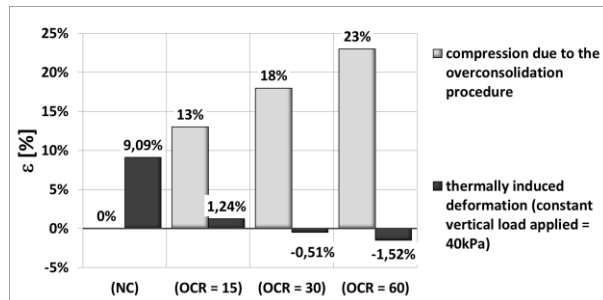


Figure 2: The thermally induced deformations measured in case of overconsolidated samples (tested soil BM_S3).

3.2 Water content and vertical permeability

The variations in the sample weight measured at the beginning and at the end of the tests show that the FT processes also lead to an irreversible loss of moisture. The water migration along the thermal gradient towards the freezing zones results in a transformation of the loosely-bonded water molecules in almost free water molecules. Their impossibility to restore the prior electrical bonds with the solid particles is due to the displacement provoked by the water migration during the ice lenses formation phase. This fact allows the expulsion of a greater amount of water during the thawing phase due to the action of the vertical load.

Effectively, for all the tested specimens, the water content measured at the end of the test (i.e. after 10 FT cycles) is almost equal to the plastic limit, while the preparation procedure fixes the water content at the beginning of the test approximately equal to the liquid limit. Therefore, it seems that the amount of water that can be involved in the cycling FT processes is almost equal to the plasticity index.

In general, ss regards the changes in hydraulic

conductivity due to FT cycles in NC natural silty clays, Chamberlain and Gow (1979) for the first time observed an increase in vertical permeability. The increase occurs despite the induced consolidation process and the subsequent decrease in void ratio (Othman et al., 1994; Qi et al., 2008; Sterpi, 2015). This effect is ascribed to the particles reorganization and to the enlargement of the bigger pores caused by the growth of iced zones. In addition they infer that the vertical development of interconnections between pores in the thawing step could lead to the formation of a pattern of paths of reduced flow resistance. All the authors complied that the increment in vertical permeability increases with the number of FT cycles. This issue needs to be further investigated with regard to possible FT cycles induced by BHEs.

4. DISCUSSION AND CONCLUSIONS

The literature overview and the experimental results demonstrated that the BHE's thermal stress could affect the clayey sediment properties if freezing-thawing (FT) cycles occur in the sediments next to the probe.

If FT cycles are established in the ground due to the working BHE, from the obtained results it can be gained that a significant irreversible settlement is induced in the NC cohesive layers in the BHE proximity:

1. The induced strain is significant (up to 9%) and irreversible.
2. This effect is higher in the shallower layers and diminishes with increasing the deposits' depth (the applied load) but, nevertheless, it occurs also under high stresses (up to 800kPa).
3. Moreover, the induced deformation appears to increase with higher salinity concentration, despite the increasing salt content lowers the sediment freezing temperature.
4. The induced volumetric alteration, combined with the progressive loss of moisture, may lead to voids formation along the probe. The effects of this on the heat exchange performances of the probe-ground system have not yet been investigated.

In addition, several authors highlighted that, in general, FT cycles can increase the vertical permeability of NC clayey sediments.

Despite the induced frozen condition is quite restrained close to the borehole (Dalla Santa et al., 2016c), the sensitivity of cohesive sediments to thermal variations has to be considered in the GSHP design and running, avoiding freezing conditions in cohesive sediments where it is possible.

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