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# Thermal Hazard on Clayey Sediments Induced by a Borehole Heat Exchanger

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**ABSTRACT**

The heat exchange of a borehole heat exchanger (BHE) of a closed-loop geothermal system alters the natural thermal status of the subsoil. An incorrect design of the ground BHE array or particular working conditions related to climatic forcing in cold areas can require the reduction of the BHE carrier fluid working temperature below 0°C, in order to increase the ground thermal withdrawal in winter.

The subsequent seasonal freezing-thaw cycles induced in the subsoil surrounding the BHE produce irreversible processes in cohesive sediments as changes in soil texture and non-negligible settlements. This behavior is particularly hazardous in environments showing abundance of cohesive layers in the subsoil.

A case-study in the Venice area (Italy) is considered, representing a typical geological context of floodplain, coastal and lagoonal areas. The changes in the mechanical behavior caused by thermal stress on representative samples of venetian typical cohesive soils was studied by using a purpose-built thermostatically controlled oedometer.

The research focusses on the role of the pore water salt contents, in order to point out a way to prevent the subsoil thermal hazard due to a working BHE system in critical contexts.

## 1. INTRODUCTION

In recent years the exploitation of low-enthalpy geothermal resources for building conditioning is growing increasingly, so that more detailed studies on their environmental effects are required. In particular, the analysis of the alteration of the natural thermal equilibrium of the subsoil surrounding a BHE field needs to be further developed, investigating its physical-chemical characteristics and the consequences on its mechanical behavior.

Generally a closed loop system for building conditioning is formed by a field of vertical BHE inserted into the ground. A carrier fluid flowing into the BHE provides the heat transport between the ground and the building. The system is controlled by a reversible Ground Source Heat Pump using electrical energy, providing also an extra heat supply when required. In winter heat is extracted from the ground, conversely in summer heat is released into the ground. As the carrier fluid exchanges heat with the surrounding ground, it alters its natural thermal status in a limited area around the borehole. Generally the probes are about 100 meters deep, and significant thermal variations occur only at a few meters from them. A balanced seasonal operation assures to limit the thermal alteration of the ground. The summer heat transfer into the subsoil recharges the thermal resource.

Thermal energy demand depends firstly on latitude, altitude and local climatic conditions, and secondly on the building's characteristics as type, use, internal thermal loads and insulation levels of external surfaces. In some cases a particular loads' imbalance of heat exchange occurs in winter, caused for example by particular seasonal constrains. Moreover, BHE fields may be designed incorrectly, undersized by reducing the number of BHE to lower installation costs. In these cases, it may be necessary to lower the carrier fluid working temperature below 0°C in order to increase the thermal withdrawal from the ground. While generally the carrier fluid may be pure water, in this case it is necessary to add anti-freezing fluids in order to enable the lowering of the BHE carrier fluid working temperature even as low as -5°C in some cases. As the BHE operating temperature is extended below 0°C through the use of anti-freezing additives, it enhances the ground thermal stress. In these conditions freezing processes occur in the ground, in particular in cohesive sediments. Due to their strong electrical interactions between solid grains and moisture content, freezing processes in this kind of sediments affect irreversibly the soil texture and its mechanical properties.

The daily and seasonal cycling variation of the carrier fluid temperature, between about -5°C and +55°C, yields a cyclic thermal stress to the ground leading to a succession of freezing-thawing processes. The effects of every freezing-thawing process rolls by producing a significant total irreversible settlement (Qi et al. 2006; Qi et al. 2007). The first process is the most pervasive, while the influence of the subsequent cycles gradually fades until the 7 – 8$^{th}$ cycle when they are no longer effective (Konrad, 1979; Konrad, 1990).

This issue is particularly remarkable in dense urbanized areas rich in cohesive layers in the stratigraphic sequence. Appropriate examples are coastal areas or transitional environments, where the lack of space obliges the installation of BHE fields under buildings themselves or very close to their foundations. In this conditions the BHE induced thermal stress affect the same portion of ground on which buildings' foundations function, so that the BHE could result in induced differential settlements which may compromise the buildings' integrity.

The case-study of Venice (Italy) is studied, as representative of a coastal dense urbanized area characterized by a typical geological context with abundance of cohesive sediments. In this brackish environment, the role of the interstitial water salinity is particularly important. It affects the freezing point of the interstitial water and so the amount of unfrozen water at a given temperature. Since the freezing-thawing cycling process proceeds, the concentration of salts in the unfrozen solution is increased at every step because of the exclusion of salt from the ice phase (Marion, 1995).

In previous works, we investigated the mechanical properties variation of normally-consolidated cohesive soils due to thermal stress cycles induced by a BHE. In particular the experimental program carried out measured the settlement caused by cycling a thermal load on some representative samples of cohesive sediments of the Venetian area, considering the effect of different loads applied. The induced freezing-thawing processes have been shown to produce total irreversible settlement of about 6% of the initial sample height. The experiments were conducted by means of a purpose-built thermally controlled oedometer.

In this study, typical cohesive sediments of the Venice area have been tested under a cyclic thermal load, with a constant vertical load applied. In order to study the effect of the cyclic thermal stress on the moisture salt concentration, we remoulded the sample using a solution of deionized water and a defined amount of NaCl. The main objective of this study is the analysis of the effect of the interstitial salt concentration and its consequence on the freezing-thawing process occurring in the soil.

### 1.1 Freezing-Thawing Processes of Soil

The study considers in particular cohesive sediments because of their strong electrical interaction between the negatively charged clayey particles, positively charged (hydrated) ions and the interstitial water molecules. This electrical bond results in a strong alteration of the soil texture when moisture undergoes phase changes. The so-called electric double layer presents a shell-like structure, imposed by the strength of the bond which depends on the proximity between water molecules and particles' surface. At a temperature slightly below 0°C free water molecules start to freeze forming ice lenses in the center-most part of the pores. Since the freezing conditions endure, the ice lenses act as freezing cores attracting the loosely-bonded adsorbed water molecules (Chamberlain & Gow, 1979), increasing the size of the ice lenses. Hence, a sort of water migration occurs towards the freezing regions in response to the induced temperature gradient (Dashjamts & Altantsetseg, 2011). Attraction forces towards the freezing regions are contrasted by the electrical attraction bonds, so that not all the water molecules in the pores freeze. The inner part of the shell-like structure formed by the strongly bonded molecules is not involved. The inner water shell remains as a liquid film (Konrad, 1989) surrounding the solid grains, providing mobility to the other water molecules. The amount of unfrozen water remaining at a given sub-zero temperature depends on several factors related to what kind of sediment (mineralogical composition, size and heterogeneity of the particles, soil texture (Pusch, 1978) and the degree of consolidation). Moreover, it depends also on moisture content and degree of saturation (Horiguchi, 1979), and on concentration and type of solute in the interstitial water (Banin & Anderson, 1974; Bing & Ma, 2011).

The freezing process changes the structure of the sediments irreversibly, leading to the formation of larger and drier aggregates and zones of iced water accumulation (Konrad, 1979; Konrad, 1990; Esch, 2004).

When the temperature rises again, melting of ice occurs. In the thawing phase, the loosely-bonded water molecules involved in the freezing process act as free water molecules. They surround the solid grains, enabling them to move easier, resulting in a significant compaction of the sample, under the pressure of a load. Moreover, the free water molecules are easily squeezed out from the porous medium, under the action of the imposed vertical load. These three contributions in normal-consolidated cohesive sediments yield an instantaneous thaw settlement (Dashjamts & Altantsetseg, 2011). In a normal-consolidated cohesive sediment, the total thaw-induced consolidation of a frozen soil is higher than the consolidation obtained in the same unfrozen soil under the same vertical load (Dashjamts & Altantsetseg, 2011).

Furthermore, the freezing-thawing process increases the vertical permeability of the soil because of the formation of vertical cracks and fissures (Chamberlain & Gow, 1979). These are formed by the increased size of the pores due to the water accumulation and freezing in the ice lenses development zones, and to the rapid expulsion of moisture in the thawing phase (Qi et al. 2006).

Hence, freezing-thawing cycles have been shown to affect the compressibility of cohesive sediments, altering their natural consolidation processes (Chamberlain & Gow, 1979; Konrad, 1989). The freezing–thawing process results in a dehydration and compaction effect (Farouki, 198; Esch, 2004). The initial soil structure can no longer be recovered (Konrad, 1979; Konrad, 1990). This leads to irreversible soil texture changes and non-negligible settlements.

In cyclic temperature conditions a significantly higher irreversible settlement occurs (Qi et al., 2006) accompanied by a densification of normally-consolidated clay samples. Furthermore, the hydraulic permeability increases at every cycle due to pore dilatation and crack formation (Chamberlain & Gow, 1979). The first cycle is the most effective, and after the subsequent fourth or fifth cycle, no significant further changes occur (Konrad, 1979; Konrad, 1990). This variation is thought to be due to the strength of the electrical bond of the water molecules available to freeze and involved in the freezing-thawing process. In the first cycle a large amount of free water molecules is available to freeze. In the following cycles, the amount of free water molecules is decreased and the process begins to involve the loosely-bonded ones, and so on. After five-seven cycles, the freezing process is more difficult to onset, modifying in size and time the evolution of the vertical strain.

#### 1.1.2 Effects of the pore solution salt concentration on the freezing-thawing processes

The most important consequences of the presence of salts in the interstitial water are the freezing-point depression and the amount of unfrozen water content. Solutes have been shown to lower the dilute solution freezing point, depending on the kind of salts and on the concentration. Considering a dilute solution with a known salt concentration, as the temperature reaches the freezing point, ice begins to precipitate largely as a pure phase, resulting in an increased concentration of the salt in the remaining solution. The freezing temperature of the remaining solution decreases due to the increased salt concentration.

Considering cohesive soils, the pore solution theory could not be sufficient to explain the effect of the presence of salts in the interstitial water (Yong et al., 1979) because of the strong electrical interaction between soil particles and pores solution. The major effects on the freezing-thawing process due to the presence of salts in the pore water are the freezing-point depression and the increase of the unfrozen water amount, depending on characteristics of soil such as texture, mineralogical composition, grain size, temperature, solute concentration and adherence of water to soil particles (Marion, 1995). Yong et al. (1979) underline that the presence of salts in the pore solution introduces two factors, acting on the two different kinds of water molecules: free in the bigger pores or electrically bonded to the particles. On one hand, the presence of salts leads to the reduction of the volume of water influenced by the electrical attraction. The bonded water film is flattened by the stronger interaction between surface forces and dissolved solutes. This factor, taken alone, will reduce the unfrozen water content. On the other hand, the free solution way of freezing is altered because of lowering of the freezing point and the consequent amount of unfrozen water increase. The first effect predominates at very low concentrations and in active clays, while the second effect prevails in general. Hence, the presence of salts in interstitial water and the exclusion of solutes by ice during the freezing process increases the concentration in the remaining solution, so that its freezing point is lowered.

Furthermore, the presence of salts in the interstitial water affects also the water molecules migration within the porous media. In a frozen porous media at sub-zero temperature, water movement occurs in response to gradients of temperature (from warm to cold areas), solute concentration (from low solute concentration to high-solute areas) and hydrostatic pressure (from high-moisture to low-moisture zones) (Perfect, 1991; Marion, 1995). As ice forms, the exclusion of salts from the ice formation increases the solute concentration in the unfrozen water. Solutes tend to accumulate in front of the advancing freezing-front, increasing the concentration gradient that attracts moisture to the freezing front.

Despite these two factors, the dominant consequence of the salts presence in the interstitial solution is a general reduction in soil hydraulic conductivity (Chamberlain, 1983), which is reduced also by the lower temperatures (Perfect, 1991) which overwhelms the other effects. As a consequence, water flux to the freezing front is generally reduced by the presence of solutes (Marion, 1995).

The strong electrical interaction acting in the diffuse double-layer around clay particles causes the matrix to turn semi-permeable. While water molecules are able to move, solutes may be restrained from moving through the liquid film because of their strong bondage (Perfect, 1991). The effect of the concentration gradient on unfrozen solute transport depends greatly on the clay fraction of the soil and on the thickness of the liquid films.

## 2. MATERIALS AND METHODS

### 2.1 Geological Background of the study-case area

The Venetian area presents a lithostratigraphic sequence formed by alluvial and lagoonal deposits, rich in cohesive sediments and characterized by a complex and highly variable lithostratigraphy, both in depth and laterally. The paleoplain consists of alluvial sediments deposited during the Pleistocenic phase of sea level lowstand, composed by a sequence of continental clays alternating with sandy sediments forming a multistorey sandbody. The uppermost deposits, at about 7-11m of depth, form an over-consolidated cohesive layer, much harder and resistant to deformation than the underlying deposits. This layer is known as *caranto* (Donnici et al., 2011), and its formation started about 18,000 years BP by subaerial exposure under an increased warm and moist climate. Furthermore, this layer represents an important time reference as it marks the unconformity separating the lowstand alluvial deposits from subsequent more superficial layers made of Holocenic lagoonal and marine deposits. These layers, deposited during the marine ingression in the Venetian area during the Middle Holocene sea level highstand phase, are rich in organic matter and formed by cohesive materials alternating with sands.

Finally, a simplified lithostratigraphic sequence of the Venice area is formed by a first level of infill land (0m,-5m), a second level of Holocenic marine clays and silts alternating with sands (0m,-11m), the over-consolidated cohesive layer known as *caranto*, and finally the Pleistocenic continental deposits of cohesive sediments alternating with sandy sediments.

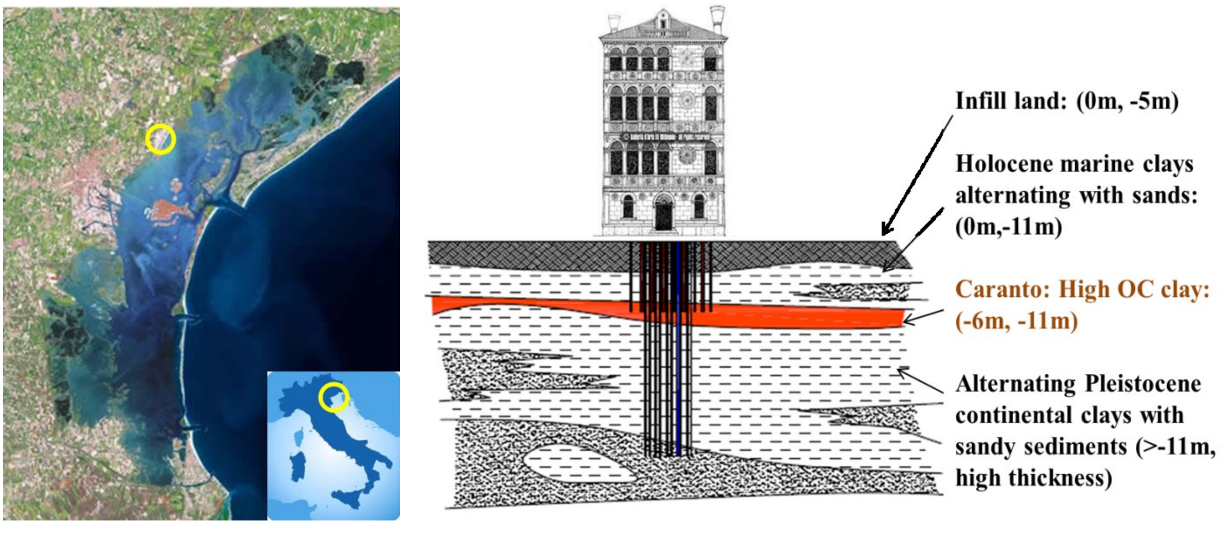



**Figure 1: The Venice lagoon (Italy) with the sampling area. On the left, the typical litostratigraphic sequence of the area.**

### 2.2 Experimental Technique and Sample Preparation

The experimental program accomplished measures the vertical deformation of a sample subjected to a thermal cyclic stress, under a constant vertical load. The tests were carried out using a standard oedometer inserted in a thermally controlled box of insulating material. The experimental system is a purpose-built experimental device, developed at the Department of Geosciences of the University of Padua in collaboration with CNR - IGG (National Research Council, Institute of Geosciences and Georesources). It consists of an environmental box with a standard oedometer within, surrounded by an anti-freeze liquid. An electronic control unit imposes the desired temperature regulating 12 Peltier cells, stabilized by a system of fresh water circulation. The stressing temperature conditions consist in a cyclic temperature variation between the values of -5°C and +55 °C, since these are the carrier fluid extreme operating temperatures when anti-freezing fluids are used. The temperature and the vertical settlement of the sample were continuously measured. A constant vertical load of 40kPa was applied. A test carried out in order to evaluate the thermal dilatation of the consolidation cell shows that the thermal deformation is comparable to the measurement errors on settlement, as preceding studies have shown (Towhata et al., 1993).

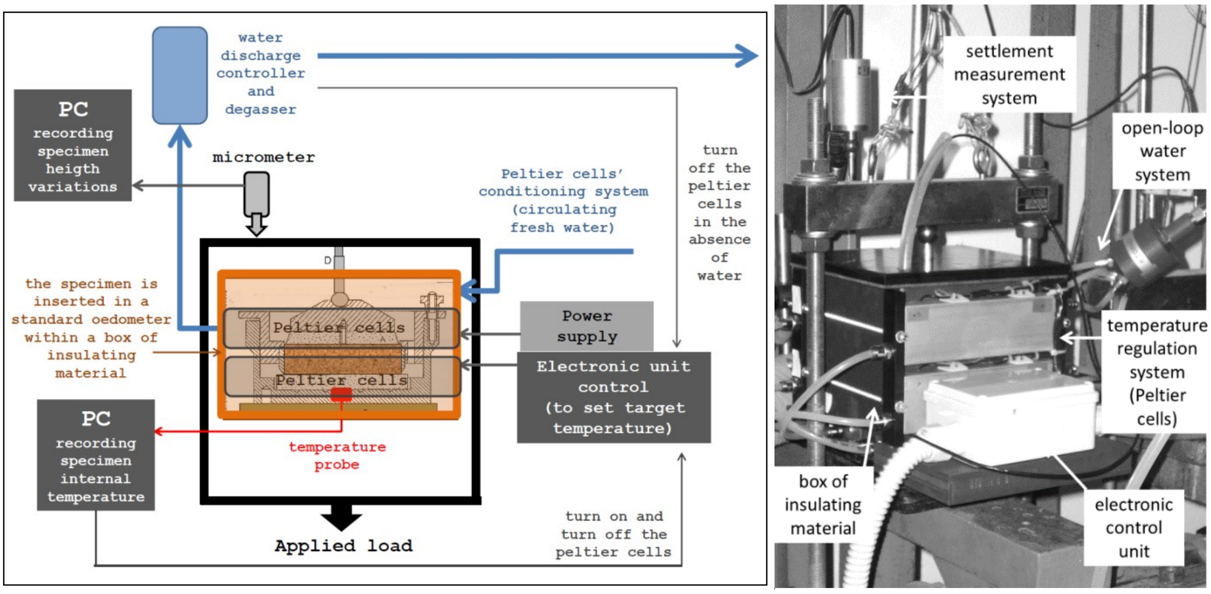
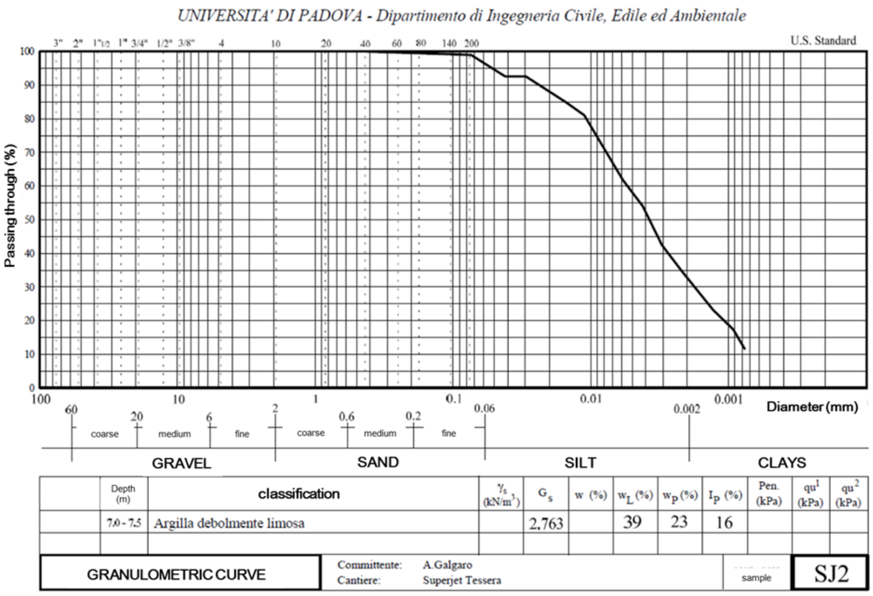



**Figure 2: Conceptual diagram of the experimental system.**

2.2.1 Properties and composition of the tested soil

The soil used for the test was collected at a depth of 7.0-7.5 m below mean sea level in an area near the lagoon coast. The sieve analysis classified it as a weakly silty clay, with a liquid limit of 39% and a plastic limit of 23%. The specific gravity is 2.763 and the organic content is 2.0%. The X-ray diffraction analysis (Barahona Fernandez, 1974), validated by comparison with chemical analysis by X-ray fluorescence, showed a mineralogical composition made of 30% of pyillosilicates (chlorite, illite, and small smectite components), carbonates (15% dolomite and 42% calcite), 11% of quartz and 2% of feldspars. Such mineralogical values confirm the data reported in previous studies on similar lithologies in the area (Tosi, 2007).




| ATTERBERG LIMITS | | MINERALOGICAL COMPOSITION | |
|---|---|---|---|
| liquid limit [%] | 39 | pyillosilicates [%] | 30 |
| plastic limit [%] | 23 | quartz [%] | 11 |
| plasticity index | 16 | calcite [%] | 42 |
| | | dolomite [%] | 15 |
| organic content [%] | 2,0 | feldspars [%] | 2 |
| Gs | 2,76 | | |
| clay fraction | 33% | depth from g.l. | 7,0 - 7,5 |

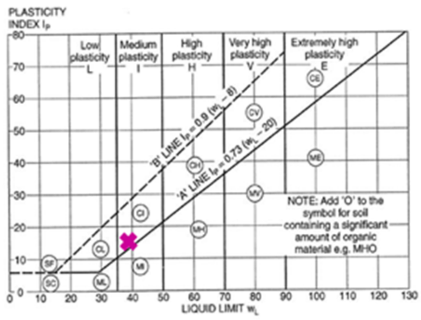



**Figure 3: Properties of the tested soil**

In order to test the effect of a known salt concentration pore water on the evolution of the specimen vertical deformation due to freeze-thaw cycles, we studied a natural soil deprived of the natural soil pore water. Hence, during sample preparation, the material was subjected to a sort of soil washing, in order to eliminate the natural salt content of the pore water. The operation was made by mixing 1.5kg of material with 5l of water, letting it settle for a week, and then removing the water on the surface. The same procedure was repeated 3 times. Afterwards, the sample was washed for the last time in a centrifuge (4000 rpm for 20 minutes) with deionized water, and left to dry at room temperature.

In addition, we prepared a known salt concentration pore solution, dissolving a specific amount of NaCl in 1l of deionized water. Finally we remolded the sample, adding the specific water to the washed soil. The water content of the remoulded sample was 35.4%.

## 3. EXPERIMENTAL RESULTS AND DISCUSSION

The variation in height of the sample tested remoulded with a solution of deionized water with 70g/l of NaCl, is shown in figure 4. The dotted line depicts the variation of the sample height, while the continuous line depicts the imposed temperature. Dots represent a measure of the height, registered at a variable frequency by means of a micrometer positioned above the oedometer bar. The temperature is measured at the same time by a probe inserted into the oedometer, at the bottom of the sample.

The effects of the thermal loading cycles on the specimen height are clearly visible on the graph. Every freezing-thawing cycle leads to a cyclic variation of the specimen height. After the drop in temperature slightly below 0°, an instantaneous rapid increase of the specimen volume is measured due to the moisture freezing process. At first, the volume increase is rapid, while the process is involving the free water molecules immediately available to ice. In a second time, the volume changes very slowly, while the process involves the loosely-bonded molecules. When the temperature rises again, the thawing process results in an instantaneous settlement due to the melting of the ice, with further a compaction of the solid grains, and the ejection of part of the moisture. The final specimen height is smaller than before the freezing-thawing process, and the initial height can no longer be recovered, demonstrating that the freezing-thawing process affects the soil texture irreversibly.

During the second temperature variation, the same processes are repeated. At every cycle an irreversible gradually less intense deformation occurs.

According to literature (Banin and Anderson, 1974; Bing and He, 2010) the exclusion of solutes by ice formation at every cycle, results in increasing the solute concentration in the unfrozen water, so that the pore solution freezing point decreases further and the amount of unfrozen water at the following cycle increases. This effect proceeds until the eighth cycle, when the thawing phase starts while the imposed temperature is still -6°C. After this cycle, the imposed freezing temperature does not appear sufficient to freeze the sample totally, and the measured height variation is very restrained.

Finally, the thermal stress is not able to induce further deformation and the specimen achieves a new stability, characterized by the absence of further irreversible settlement, and by the unavailability to freeze further. The total irreversible deformation registered due to the thermal cycling load is about 9% of the specimen initial height.

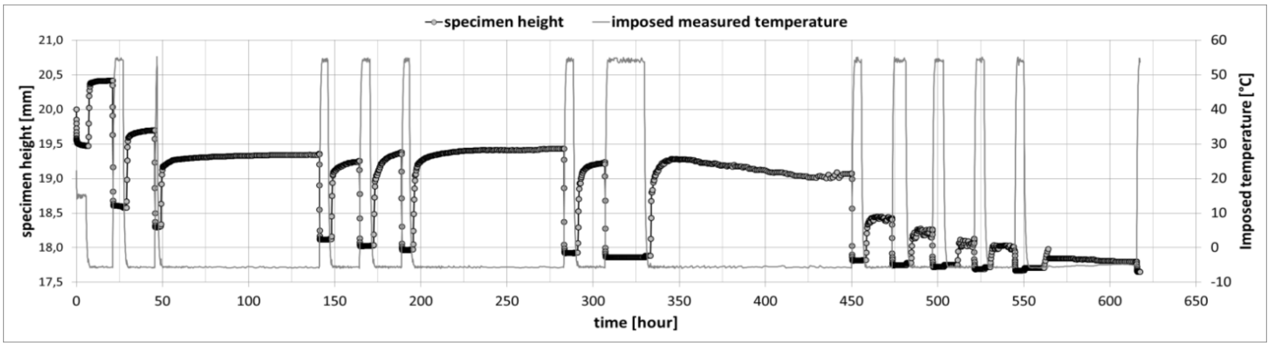



**Figure 4: Variation of specimen height in time, under a thermal cycling stress - sample tested remoulded with a solution of deionized water with 70g/l of NaCl**

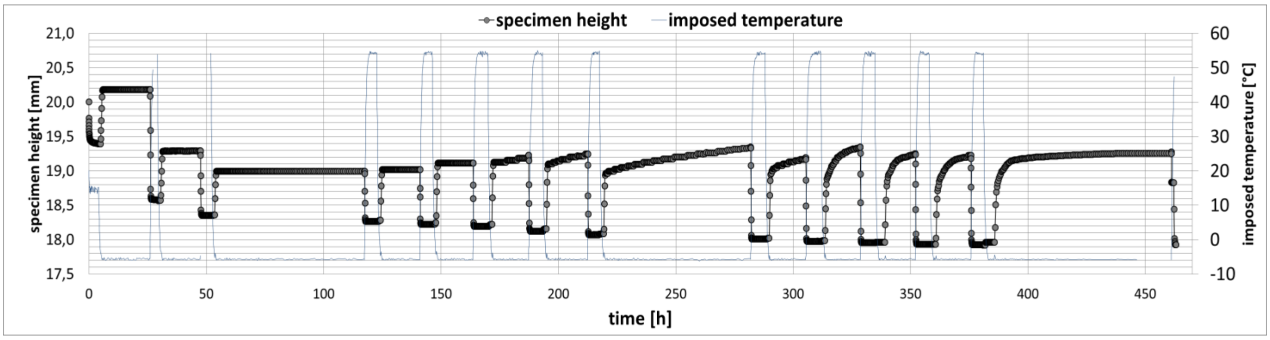



**Figure 5: Variation of specimen height in time, under a thermal cycling stress - sample tested remoulded with deionized water.**

The comparison between the sample remoulded with a solution of deionized water with 70g/l of NaCl and the same sediment remoulded with only deionized water (with an initial water content of 34.4%), demonstrates clearly the effect of salt concentration on the interstitial water due to the salt exclusion from ice formation. The sample without salt in the pore water reaches the new equilibrium where no more irreversible settlements are registered after 8-9 freezing-thawing cycles, but the sample can still be frozen.

The freezing and thawing temperatures measured at every cycle show the phase change point depression due to the increasing concentration of salts during the cyclic process. At the first cycle the freezing temperature is around -4°C, while in the final cycles the imposed temperature of -6°C is not sufficient for freezing to occur. The electrical conductivity measured in the water extracted from the tested sample by means of a centrifuge before and after the experiment are respectively 33500µS/cm and 42100µS/cm, an increase of about 26%.

## 4. CONCLUSIONS

This research represents an attempt to apply the knowledge of the freezing-thawing process in the subsoil to the design of BHE arrays and their exploitation in a sustainable way.

Previous studies demonstrated that when the below-zero temperature of the heat carrier fluid in a BHE induces freezing-thawing cycles in the subsoil, thermal alteration of the ground could affect the mechanical properties of cohesive sediments, altering their natural consolidation process.

In particular, this research analyzes the effect of the presence of salt in the pore water, demonstrating that the salinity concentration in interstitial water of a soil is a critical element, influencing the freezing-thawing behavior of the ground surrounding a BHE. This issue is particularly remarkable in coastal and dense urbanized areas rich in cohesive layers in the subsoil, where the lack of space obliges BHE installations very close to buildings' foundation, as in the considered case-study. Moreover, due to salt exclusion from ice formation, pore water salinity concentration has been shown to increase at every freezing-thawing cycle, lowering the sediments freezing point.

Hence, we can conclude that in coastal and transitional areas like Venice, the effect of the presence of salts in interstitial solution is generally in favor of safety. However, these areas and environments are often characterized by an extremely complex and highly variable lithostratigraphy both in depth and laterally, combined with a highly changing salt concentration in interstitial water, requiring an in-depth knowledge of the local geological conditions.

For this reason, despite the positive effects guaranteed by the brackish environment, we suggest to maintain the mean carrier fluid temperature above 0°C in order to avoid freezing conditions in the ground. Otherwise, BHE fields should be designed as far as possible from buildings' foundations in order to reduce the thermal geotechnical hazard.

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