IRREVERSIBLE SETTLEMENTS IN CLAYEY SEDIMENTS DUE TO THERMAL STRESS INDUCED BY THE OPERATION OF A BOREHOLE HEAT EXCHANGER

Ph.D. candidate: GIORGIA DALLA SANTA, I course
Tutor: Prof. ANTONIO GALGARO
Cycle: XXVIII course

Abstract

The borehole heat exchanger (BHE) of a closed-loop geothermal system exchanges heat with the subsoil, altering its prior thermal equilibrium. In densely urbanized areas, lack of open space means that BHEs are installed under or close to the foundations of buildings, disturbing also the foundation materials.The case-study of Venice is considered. The thermal response of cohesive soils was tested using an expressly made thermostatically controlled oedometer. Some representative samples of venetian typical litostratigrapich sequence were tested applying different loads conditions.

The results show that the induced thermal stress can lead to significant irreversible settlement in normal consolidated cohesive sediments, only if the carrier fluid temperature induces freeze-thaw cycles in the subsoil exceeding a lower limit that can prudently be assumed to be 0°C.

Hence, this study would suggest that 0°C be taken as a good operating temperature threshold for BHEs, to prevent significant vertical deformations.

Introduction

The use of geothermal solutions for buildings conditioning could contribute significantly to the reduction of greenhouse emissions and the avoidance of summertime electrical absorption peaks caused by traditional combustion and conditioning systems. Moreover, these solutions could help overcome the architectural constraints involved in the external installation of air-to-air chillers or cooling towers which may be difficult to install in historic buildings where the roof has limited load-bearing capacity, and may also appear ugly or too much noisy.

The most commonly used heat exchanger device is the vertical borehole heat exchanger (BHE), which is inserted into the ground, coupled with a heat pump which transfers the heat between ground and building using electrical energy to supply necessary extra heating, in a closed loop geo-exchange system called GSHP (Ground Source Heat Pump systems). The energetic and environmental benefits are due to the fact that ground temperatures below 10 m are stable over time with values comparable to the local mean annual air temperature, functioning as a heat source in heating mode, and as a heat sink in cooling mode. Thermal energy is transferred from the ground to the building, or vice-versa, by the carrier fluid (pure water or a mixture of water and antifreeze fluids) flowing into the BHE.

Typically, BHEs reach a depth of 100-150 m. As the carrier fluid flows through the BHE, it exchanges heat with the surrounding ground altering the prior thermal equilibrium in a limited area around the borehole [Banks, 2012].The demand for energy depends on the local climatic conditions, on the building's use and its internal loads, as well as on the insulation levels of the opaque and glazed surfaces. A relatively common practice is the use of antifreeze additives which allow the carrier fluid to reach temperatures as low as -5°C in some cases, with a consequent reduction of BHE length in order to reduce installation costs. However, such low temperatures cause higher thermal stress to the ground.

If the BHE operating temperature is extended significantly below 0°C through the use of antifreezing additives , freeze-thaw cycles occur in the ground. The freezing and the subsequent thawing modify the deformability of cohesive sediments, altering their natural consolidation processes [Chamberlain & Gow, 1979, Konrad, 1989]. Moreover, if winter heating and summer cooling are not well-balanced, the cyclical thermal loading could lead to a progressive lowering of the minimum carrier fluid temperature.

Aim

The issue of this research is the investigation of the mechanical effects due to the thermal stress induced by a BHE system on the compressibility of cohesive sediments and the estimation of a temperature limit value for the carrier fluid in order to avoid induced settlements. The topic is very remarkable specially in densely urbanized areas, where BHEs have to be bored very close to the buildings because of the lack of space, the buildings' stability can be compromised. The historic centre of Venice is particularly affected by this problem because the city is built on small islands surrounded by lagoon water, and the lithostratigraphic sequence is characterized by an abundance of cohesive levels [Donnici et al., 2011].

The mechanical behaviour of typical Venetian cohesive sediments under thermal loading cycles was studied in laboratory tests by using an expressly made experimental device, consisting of a standard oedometer inserted in a thermostatic cell where the temperature could vary between -5°C to +55 °C, like the operating temperature range of an undersized BHE field.
Finally, in order to evaluate the distribution and evolution in time of thermal plume induced by a BHE in the ground, a numerical model was used in collaboration with Giordano Teza, developing a thermal analysis in a case study of a real building in Venice, taking into consideration both optimal and reduced (therefore creating higher thermal stress) BHE lengths.

Mechanical behaviour of thermal stressed cohesive sediments: background

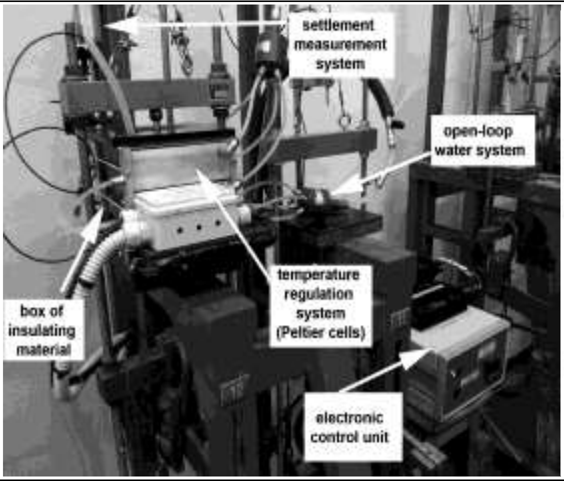
A saturated soil consists of solid grains and water. The interactions between the pore water, the cations present in the pore water and the negatively charged clayey particle surface form the so-called electric double layer and the adsorbed water. The intensity of the bond between the water molecules and the particle surface decreases with distance, depending on the closeness and electrical interactions, so that water molecules are free to move only if they are far enough from a solid particle, otherwise they are bonded to the solid particle untill they are strongly held in the case of close proximity to the particle surface. Hence, the particle with the surrounding adsorbed water layers may be ideally figured as a shell-like structure.
The freezing point of soil is a function of its water content, salt content and imposed load [Bing et al., 2011]. If the ground temperature changes and falls few degrees below 0°C, formation of ice lenses begins, initially involving the free water inside the centre-most part of the pores. If free pore water is unavailable, the formation of ice lenses cannot occur [Horiguchi 1979]. The lenses act as crystallization centres and attract the loosely-bonded adsorbed water molecules, starting with those less bonded to the solid grains, so that a sort of migration of water molecules is established from the cold areas towards the ice lenses along the thermal gradient [Chamberlain & Gow, 1979], with a consequent growth in ice lenses [Dashjamts & Altantsetseg, 2011]. The change in the water's state does not involve the inner water shells because of their strong electrical bond with the solid grains. These liquid films provide mobility to other molecules [Konrad, 1989].
Therefore, a frozen soil consists of solid grains, solid ice and unfrozen water. The amount of unfrozen water at a certain temperature mainly depends on textural features (particle size, roughness, structure of solid aggregates and pores [Pusch, 1979]), mineralogy, soil pH and pore water chemistry [Konrad, 1979, 1990].
The freezing process acts on the soil structure irreversibly. In the colder parts of the soil, the grains lose moisture leading to the formation of larger and drier aggregates with a dehydrating/compaction effect. In the freezing pores the ice lenses grow, producing water confinement. Rearrangement of the soil is an irreversible process and the prior soil structure can no longer be recovered [Konrad, 1979, 1990, Dashjamts & Altantsetseg, 2011].

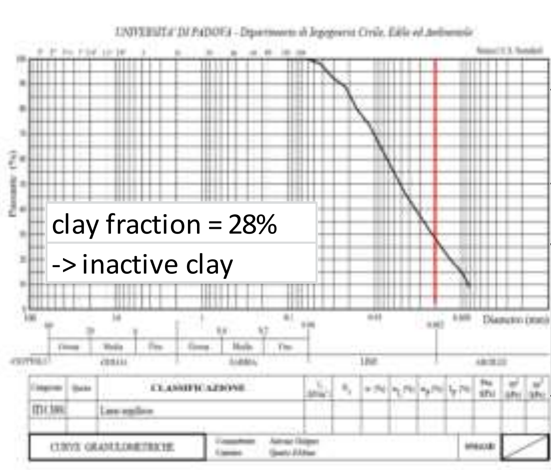
If a frozen soil is heated, when the temperature reaches melting point, an immediate thaw settlement is observed. The ice melting causes an instantaneous decrease in volume. The water molecules are unable to restore the previous electrical bonds with the solid grains, so that after a freeze/thaw cycle a significant transformation of loosely-bonded water in free water occurs [Dashjamts & Altantsetseg, 2011]. These free water molecules surround solid aggregates, enabling them to slide more easily over one another, leading to a further significant consolidation. Moreover, this water can easily leach from the porous medium. The thaw settlement stops when the water molecules are finally squeezed out and a new equilibrium according to the principle of effective stresses is achieved. 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].

In cycling temperature conditions a higher significant irreversible settlement occurs [Qi et al. 2006, Qi et al. 2008] and at every cycle the vertical permeability is increased, caused by both pore dilatation and crack formation [Chamberlain & Gow, 1979], while the moisture content of the soil decreases. Moreover, the salinity of the unfrozen water increases every cycle, as a result of a sort of freezing-induced distillation process. The first cycle is the most effective [Konrad, 1979, 1990] because a large amount of loosely-bonded water is available. In the subsequent cycles, the freezing process is progressively concerned with water molecules which are increasingly bonded to clay particles, and the quantity of water involved in the process gradually decreases. After the fourth or the fifth cycle, no significant further changes occur [Konrad, 1979, 1990].

Laboratory testing setup

The experimental program consisted of tests conducted by means of a thermally controlled oedometer, expressly conceived, developed at the Department of Geosciences in collaboration with CNR - IGG.
The consolidation cell of the oedometer (7.05 cm diameter and 2 cm high) was placed within a thermostatically controlled box made of insulating material, surrounded by an anti-freeze liquid. Four Peltier cells permitted accurate temperature regulation, stabilized by a system of water circulation, by means of an electronic control unit. The temperature and the vertical settlement of the sample were continuously measured. 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 previous studies have shown.





ATTERBERG LIMITS	
liquid limit [%]	32
plastic limit [%]	21
plasticity index	11
MINERALOGICAL COMPOSIT	
pyillosilicates [%]	23
quartz [%]	17
calcite [%]	26
dolomite [%]	28
feldspars [%]	7
organic content [%]	2,4

Figure 1a: Experimental setup for the oedometer tests in thermally controlled conditions.
Figure 1b: mineralogical and geotechnical characterization of the soil tested (The mineralogical composition was evaluated by X-ray diffraction and validated by comparison with chemical analysis by X-ray fluorescence).

The soil tested was collected between 1.80 and 5.50 m below mean sea level in an area near the lagoon coast. It is a quite normal consolidated clayey-silt, belonging to the Holocenic marine strata.
Remoulded samples are tested in the experimental device after a pre-consolidation of 72 hours, under a vertical stress equal to the one of the test. Two loads were used: 40kPa, which reproduces the average in-situ litostatic stress in a saturated condition, and 200kPa, which represents an overload in order to evaluate the effect of a higher overburden pressure or the presence of a building above ground level. Two kinds of oedometer test were carried out into the thermal cell, after a first stage of 12 hours at temperature of 15°C: in type (1) tests the temperature was varied from 15°C (the reference temperature) to one of five different temperatures T* (respectively 55°C, 30°C, 15°C, 5°C, 0°C and -5°C), with the application of a load of 40kPa; in type (2) tests the material was subjected to several 24-hour thermal cycles [-5°C +55°C].

In order to evaluate the size and evolution of the BHE-induced thermal plume in the ground, the case of a typical Venetian building was studied (Palazzo Grassi). The heating and cooling loads are computed according to the standards ISO 13790:2008, taking into account the building features (materials, dimensions, uses ecc..). We used EED to design the BHE field and implemented a finite element model.

Results and discussion

Type (1) tests show that only the -5°C curve significantly differs from the reference curve (T = 15°C), showing a rapid increase in the void ratio of about 15%, which corresponds to a significant expansive strain and an increase of 7.6% in height. The initial expansion ratio is very sharp, while after an hour the slope decreases until it reaches a fairly steady state, probably because of the different strength of the water-particle bonds affected by phase change.

Type (2) tests show the specimen behaviour during 7 freeze-thaw cycles, leading to a final significant total compression. As expected [Konrad, 1979, Pusch, 1979], the thaw settlement occurs at every thermal cycle with a different intensity, and after the fourth or fifth, the thermal cyclic stress seems unable to generate further significant irreversible changes. In both the figures also show that the strain rate slightly decreases cycle after cycle, highlighting that the formation of ice lenses becomes progressively more difficult, because of the strength of the bond between grains and water molecules involved in the process and an increase in the salinity of the residual unfrozen water [Bing et al., 2011]. The results highlight that the lower the applied load is (overburden pressure), the more developed the expansion during the freezing process, and the higher the subsequent thawing compression Nevertheless, the share of settlement produced by the cyclic thermal stress is approximately equal in the two cases (almost 6% of the initial thickness of the specimen).

The numerical modelling of the behaviour of a BHE field designed to satisfy the heating/cooling needs of a typical Venetian historical building, shows that the carrier fluid temperature never reaches +2°C, provided the system is well designed and the BHE length is optimal. If the BHE length is lowered by 30% of the optimal value to reduce the initial costs, the radius of the area whose temperature is less than -3°C is about 10 cm, slightly larger than the BHE radius (7 cm).

Conclusions and future works

The main conclusions are: (i) the normal consolidated cohesive sediments like those in Venice are sensitive to the thermal alteration caused by a BHE system only if the carrier fluid temperature exceeds a lower limit that can prudently be assumed to be 0°C; (ii) if the temperature limit is exceeded, freezing can affect the pore water leading to an accumulated irreversible strain of about 6% regardless of the mechanical load applied (in the tested range); (iii) numerical simulations show that the limit is never exceeded in the case study of a typical historical Venetian building, even if the winter heating needs exceed summer cooling needs by 25%, provided that the BHE is well-designed; (iv) if, however, the BHE length is undersized, the carrier fluid temperature exceeds the threshold value.

Therefore, low enthalpy geothermal solutions can also be exploited in a very sensitive environment like Venice, but the use of antifreeze carrier fluids coupled with the reduction of the BHE length can lead to structural damage and therefore must be avoided.

Future studies will deal with a further geomechanical characterization of the cohesive sediments for different degrees of overconsolidation and an analysis of the effects of different concentrations of pore water salinity. Moreover, we aim to achieve a quantification of the structural damage to buildings due to invalid design of geothermal systems and an estimation of the maximum density of geothermal systems which is admissible in highly urbanized areas.

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SUMMARY OF ACTIVITY IN THIS YEAR

***Courses*:**

RANALLI G.: “Geodinamica”, Dipartimento di Geoscienze, Università degli Studi di Padova.

CALANDRUCCIO E. : “Spoken English”, Dipartimento di Geoscienze, Università degli Studi di Padova.

GULLICK L.H.: “Corso avanzato di inglese scientifico”, Dipartimento di Geoscienze, Università degli Studi di Padova.

SALMASO L.: “Statistica”, Dipartimento di Ingegneria Industriale, Università degli Studi di Padova.

ROSS A.: “ Scientific Communication, Dipartimento di Geoscienze, Università degli Studi di Padova.

***Posters*:**

GALGARO A., FARINA Z., CULTRERA M., DESTRO E., **DALLA SANTA G**., DI SIPIO E.: *Feasibility analysis of a Borehole Heat Exchanger (BHE) to be installed in high geothermal flux area: the case of Euganean Thermal Basin, Italy –* FIST GEOITALIA 2013

***Publications*:**

GALGARO, A., **DALLA SANTA, G**., TEZA, G., TATEO, F., COLA, S.; DE CARLI, M., DI SIPIO, E., DESTRO, E.. Changes in the mechanical properties of clayey sediments due to thermal stress induced by the operation of a borehole heat exchanger. Submitted to *Renewable Energy* 25/10/2013.

Congresses and Workshops:

European Geothermal Congress, Pisa 3–7 June 2013

CORILA - Utilizzo delle ricerche nella Salvaguardia di Venezia, Venezia 23 September 2013

9th FIST GEOITALIA 2013, Pisa 15-18 September 2013

Geotermia ed energie rinnovabili nella Provincia di Verona, Verona 11 October 2013

***Teaching activities*:**

Support to thesis:

A. FORNASIERO, *Deformazioni indotte da variazioni termiche in un’argilla di Venezia* - Corso di Laurea Magistrale in Ingegneria Civile – DICEA, UNIPD. Supervisor: prof. S. Cola

L. STEFANILE, A*nalisi sperimentale del comportamento termo-meccanico di un’ argilla di Venezia* - Corso di Laurea Triennale in Ingegneria Civile – DICEA, UNIPD. Supervisor: prof. S. Cola

Co-supervisor of thesis:

N. VALENTINI, *Analisi sperimentale dei terreni coesivi della laguna di Venezia in relazione alla realizzazione di impianti di geoscambio* - Corso di Laurea Triennale in Ingegneria Civile – DICEA, UNIPD. Supervisor: prof. S. Cola

S. BOSCOLO RIZZO, *Analisi sperimentale degli effetti meccanici indotti da sollecitazioni termiche prodotte da scambiatori termici verticali (BHE) su materiali argillosi nella Provincia di Venezia* - Corso di Laurea Magistrale in Scienze e Tecnologie Geologiche, Università Degli Studi Di Pisa. Supervisor: prof. A. Sbrana, prof. A. Galgaro.