Heat storage in clay – Geotechnical consequences and use of heat drains

Stockage thermique dans les argiles – Conséquences géotechniques et utilisation de drains thermiques

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SYNOPSIS To reduce the dependence of oil for heating, one alternative is to store energy surplus in clay deposits and then use it in the winter time. The problems associated with heat storage in clay have been studied thoroughly and this paper provides a few examples of test results and observed phenomena from the extensive field and laboratory test programs. Also included is a description of the so-called heat drain which can be used for an effective heat exchange in a clay deposit.

INTRODUCTION

During the last decade, techniques for seasonal heat storage in clay have been developed in Sweden as means of reducing the dependence of oil. Experiences from pilot plants show that technical as well as ecconomic requirements can be fulfilled when storing summer heat for use in the winter.

It is a well known fact that temperature changes influence the geotechnical properties of a clay. Therefore, part of the research has been concentrated on the conditions necessary for the geotechnical consequences of heat storage in clay with respect to land-use planning and existing structures. Studies have also been conducted to improve the effectiveness of the heat exchanger in the ground.

GEOTECHNICAL INVESTIGATIONS IN THE FIELD AND LABORATORY

The changes in the geotechnical properties of a clay due to heating have been thoroughly studied at the Geotechnical Department of Chalmers University of Technology by means of laboratory and field investigations.

Field investigations

The field tests were carried out in the western part of Sweden in a lightly overconsolidated, postglacial clay, approximately 40 m in depth. Profiles of shear strength, sensitivity, water content and bulk density are illustrated in figure 1.

The clay was heated by circulating hot water in heat exchangers consisting of plastic and steel tubes, respectively, installed to a depth of 12 m, in a rectangular pattern with the dimension of 2.0 m x 2.8 m. Equipment necessary for monitoring temperatures, pore pressures and settlements were installed in the clay.

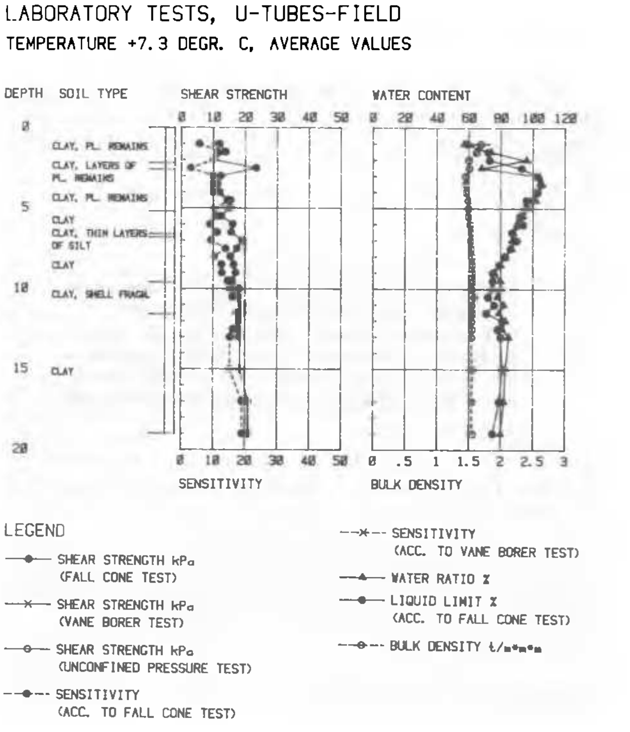

Fig.1 Soil profile for test site at Kungälv, Sweden.

Over a period of 150 days, the average storage temperature increased almost linearly from an initial value of 7°C to a final value of 22°C. This increase in temperature was accompanied by an increase in pore pressures from 5 to 16 kPa, measured at four levels within the storage and at one level below the storage. Examples of tests results are given in figure 2.
Settlements were measured with bellow hose gauges at different depths, and the results

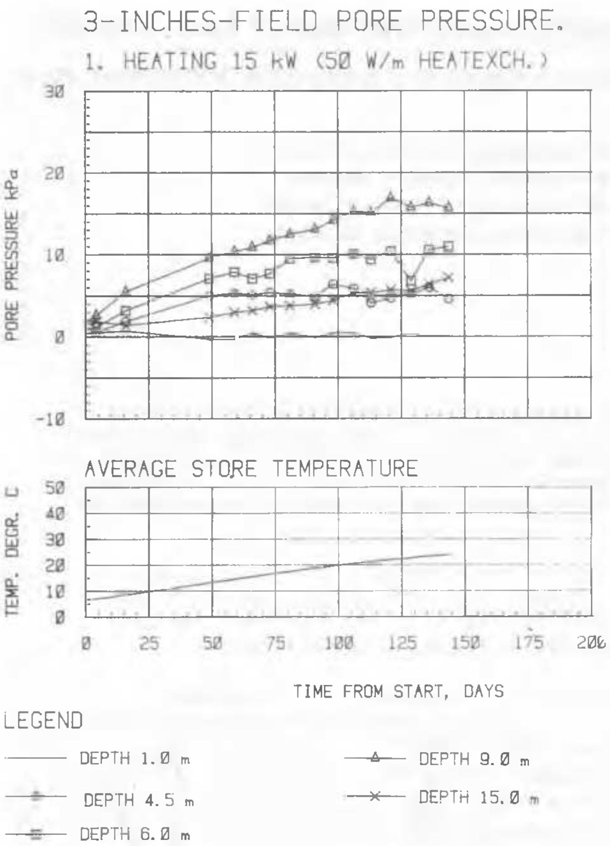

Fig.2 Induced pore pressure increase and average storage temperature at different levels measured at the midpoint between heat exchangers. In the figure data are given only for the heating period of 120 days.

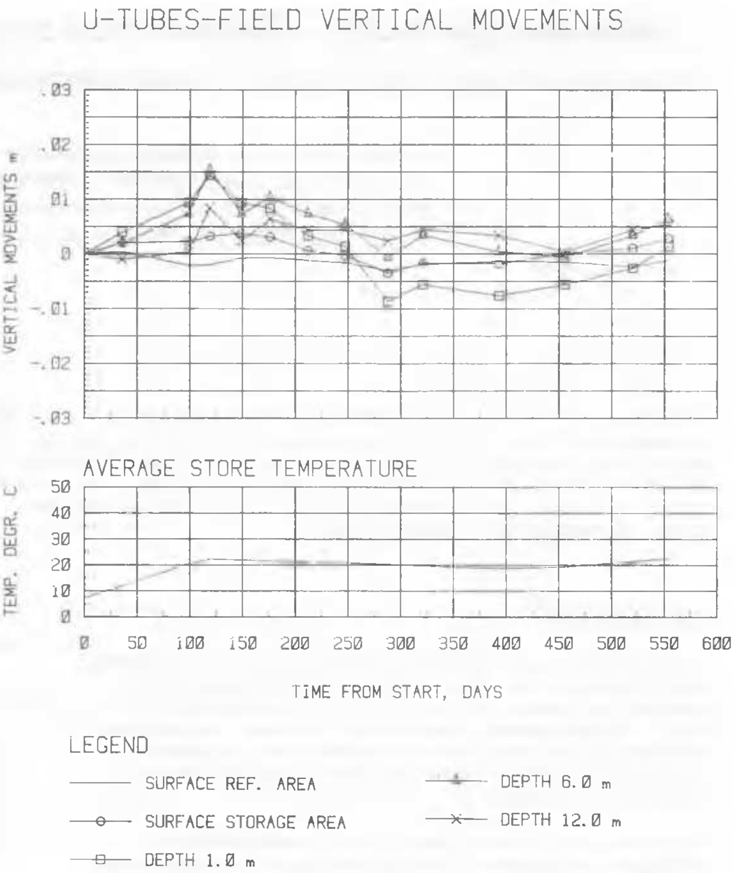

Fig.3 Settlements and temperatures.

are given in figure 3. The accuracy of the measuring system was ± 1 mm.

The observed settlements were generally small but a certain heave in the soil was observed during the heating period. The heave seemed to disappear gradually as the temperature was kept constant.

Laboratory investigations

Standard geotechnical laboratory tests were made on field samples taken prior to heating and at the end of the heating period when the average storage temperature was 22°C.

Preconsolidation pressures prior to and after heating have been evaluated from oedometer tests and are given in figure 4. The scatter in figure 4 is considerable but a regression analysis indicates that a reduction of the preconsolidation pressure may have occurred. However, in this case the effective overburden pressure in the clay was still less than the preconsolidation pressure after the heating, which is why severe settlements, caused by the heating, were neither expected nor measured.

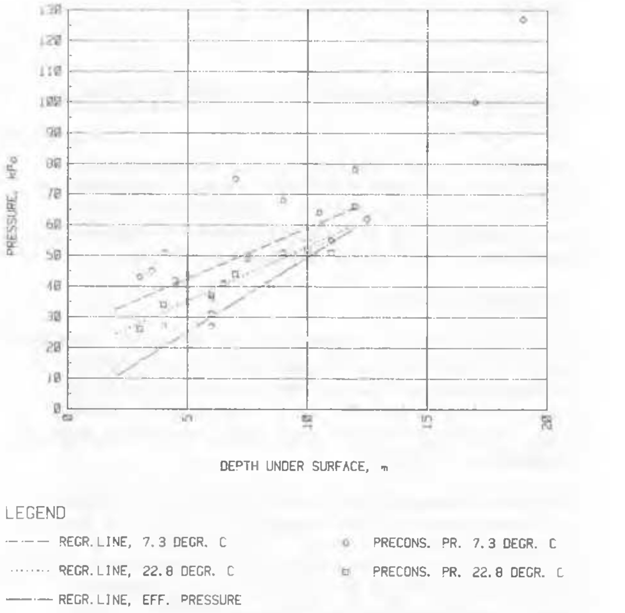

Fig.4 Preconsolidation in relation to depth.

INFLUENCE OF HEAT STORAGE ON THE GEOTECHNICAL PROPERTIES OF CLAY

When the temperature in a clay is changed, the pore pressures will change too since the water has a greater coefficient of volumetric expansion than the solids. Also, the water constitutes a larger part of the clay volume. A temperature rise (when charging a heat storage) will cause an increase in pore pressure and a corresponding reduction of the effective overburden pressure which is analogous, in effect, to the unloading of the ground. As a consequence, the soil layers will heave. Cooling of the clay (when discharging a heat storage) will reverse the process and, possibly, cause consolidation.

The results from field and laboratory tests show that the apparent preconsolidation pressure decreases when the temperature increases. The simultaneous increase of pore pressure will, to some extent, compensate this decrease. While cooling the clay, the pore water pressure decreases and the simultaneous increase of the effective overburden pressure may exceed the reduced preconsolidation pressure. If so, settlements may occur. During this process normally, or even slightly overconsolidated clays, can experience settlements without any external loading to the soil.

For seasonal heat storage the temperature varies cyclically during the year. The long term settlements will, therefore, depend on the average temperature and the extreme variations in the soil during the year.

Presently, it is not known whether the decrease of the apparent preconsolidation pressure, when heating a clay, is caused by a disturbance of the soil structure as the pore pressure changes, or if it is an effect of the increased creep rates and the increased viscosity of the water as a result of the higher temperatures. The results from the tests have not yet been fully analyzed to give a distinct answer in this regard.

It has been reported that the heating of a clay can result in a decrease of shear strength. The field tests did not indicate this effect. A possible explanation for this finding is that the temperature varies cyclicly during the heat storage process and as such, the shear strength varies inversely with temperature changes. Should the clay consolidate, and permanent settlements occur, the long term effect will be an increase in shear strength.

HEAT DRAINS

Heat exhangers in clay

The charging and discharging of heat in clay has so far been accomplished using small, vertical, plastic, U - shaped tubes. Since soft clay has a low thermal conductivity, the heat exchangers must be installed close together. To increase the thermal effectivity, a new type of heat exchanger, the "heat drain", has been developed at Chalmers University. This type of heat exchanger may also help to reduce the problems associated with the changes in the geotechnical properties of the clay.

Performance of heat drains

The heat drain consists of a conventional sand drain with a diameter of 180 - 200 mm and a supplementary plastic tube in which the fluid circulates. The plastic tube is U - shaped and spans the entire length of the sand drain (figure 5).

The heat drains will be installed by means of slightly modified equipment used for the installation of sand drains in Sweden.

A small prototype has been tested in the same test field as previously discussed and the results indicate very small changes in pore pressure to the surroundings while heating the clay. The thermal effectivity increased significantly compared with U - tubes in the clay.

In a prestudy concerning heat storage in clay for a school and a sports building, a theoretical study of the thermal and geotechnical function of the heat drain had been performed. The technique for installing the heat drains, along with their thermal and geotechnical function, will be investigated by means of full-scale testing at this heat storage site.

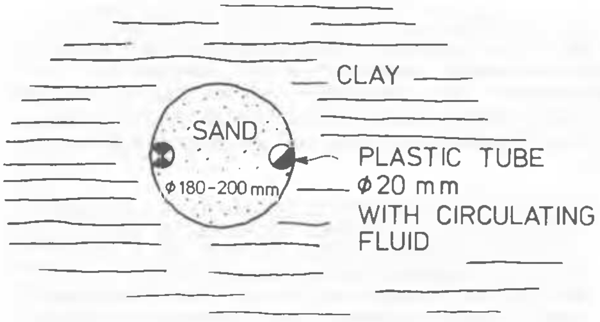

Fig.5 Horizontal cross-section of a heat drain.

Thermal function

Since clay has a low thermal conductivity, it is advantageous to use heat exchangers with as large contact areas as possible. Also, since sand has a higher thermal conductivity than clay, this reduces the heat resistance closest to the plastic tubes compared with their counterpart in clay. Furthermore, sand has a higher hydraulic conductivity (permeability) which makes convective heat transport possible in the heat drain.

Calculations, using theoretical models, show that the heat transfer capacity, at the heat drain, is 20 to 40% higher when compared with pipes in clay. The lower value corresponds to no convection and the upper value for full convection and a uniform temperature in the sand column. This will, for the same storage capacity, lead to an increase in the required distance between the heat exchangers or a lowering of the temperature difference between the fluid in the pipes and the clay. This way, lower installation costs can be obtained.

Geotechnical function

Heat drains will give rise to a more rapid water flow within the soil. When charging (heating) the storage, the heat drains facilitate the pore water pressure equalization. Discharging (cooling) of the storage will produce negative pressure in the pores, and if free water is available in the heat drains this water may possibly flow back into the clay and prevent settlements.

Settlements will most likely occur anyhow due to changes in the geotechnical properties when heating and cooling the clay. Further research may lead to a better understanding of the pore water flow during cyclic changes of the temperature and make it possible to predict the settlements.

CONCLUSIONS

Field and laboratory tests on clay, during heat storage, indicate that the pore pressures increase with the temperature. Heaving of the soil was recorded during the heating period. The apparent preconsolidation pressures decrease, somewhat, when heating a clay layer. The long term effects will be that settlements will most likely occur due to the cyclical heating and loading of the clay.

Heat drains, used as heat exchangers in clay, will increase the thermal effectivity and may mitigate some adverse effects as a consequence of changes to the geotechnical properties as a result of cyclic heating and cooling. This will make heat storage in clay more feasible from an exonomic point of view.

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