STATENS GEOTEKNISKA INSTITUT
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Field tests with heating (70 °C) and freezing of the soil

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Report 53

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Preface

This report presents the results from three years of operation, 1992-1994, of a test field for high temperature storage (70 °C) and combined heat and cold storage in soft clay. The purpose was to study the energy performance and effects on clay under the influence of store temperatures up to 70 °C and around the freezing point.

The report has both a theoretical and practical application. Theoretical outlines for the thermal behaviour of clay as well as some practical recommendations regarding design aspects are presented. At present, the development of energy supply systems is directed towards improvements of energy efficiency and greater use of renewable energy sources. Heat storage in soil is well in agreement with these intentions. Therefore, the report is of interest to a wide circle of readers outside the corps of geotechnical engineers. Prospective readers may be active in research, design and planning/construction or those interested in the field of energy storage and supply techniques for buildings.

Heat storage in soft clay has previously been utilised at moderate temperatures of about 30 °C. Higher storage temperatures may increase the technical and economic benefit of heat stores, for instance in a solar heat application. To enable better design and optimisation of ground heat stores in the future, at various temperatures, a better understanding of soil behaviour is required. Furthermore, experience from construction and operation is necessary. Especially from the user's point of view, the operation of a high temperature heat store application in soft clay must have been proven to function satisfactorily at a verified and competitive storage cost. The consequences of a high temperature application in soft clay, in terms of geotechnical and thermal aspects as well as energy performance, have been investigated in the test field.

The test field was designed and constructed by the Swedish Geotechnical Institute (SGI) with an experimental grant from the Swedish Council for Building Research (BFR). Procurement and construction of the energy supply centre was performed by external contrators using specifications from the SGI. The costs for research activities in the test field have been shared between the BFR and the SGI.

The project has been carried out by Marti Lehtmets, Anna Gabrielsson, Lovisa Moritz and Ulf Bergdahl at the SGI. It was led by Marti Lehtmets and Ulf Bergdahl. Investigations in the field and in the laboratory have been performed by other members of the SGI staff to whom the authors express their sincere gratitude. Göran Hellström at Lund University of Technology has performed simulations and evaluations of the heat transfer capacity of the ground heat exchangers and his work is highly appreciated.

First, we wish to express our thanks to the Swedish Council for Building Research through whose financial support this project was made possible. Special thanks are also given to the members of the reference group of the research programme: Björn Sellberg at the BFR, Jan-Olof Dalenbäck, Chalmers University of Technology and Heimo Zinko, ZW Energiteknik, for their continuous support in the project.

Our thanks also go to Lennart Börgesson, Clay Technology, and Gunnar Gustafson, Chalmers University of Technology, for valuable comments in the process of submitting the report. Rolf Larsson at the SGI contributed excellent comments, in particular on the geotechnical evaluation, for which we are grateful. We also wish to thank Jan Lindgren at the same institute for his careful scrutiny of the final manuscript.

Linköping, September 1996

The authors

Contents

Summary

Field tests have shown that heat storage in soft clay with temperatures up to 70 °C have good prospects for functioning adequately. The results are for the most part good and in agreement with used theoretical models. Store application comprising freezing and thawing, however, was interrupted after settlements of about two metres in parts of the store inhibited circulation in the ducts.

Ground heat storage on a long term basis is commonly used for storage of excess heat or solar heat from summer to winter. Previous studies have proved soft clay to be a cost-effective storage medium, especially if high store temperatures are permitted. High storage temperatures increase the applicability of the stored heat which may be used directly by the consumer. In Sweden, deposits of soft clay are common close to densely populated areas, sometimes with depths of several tens of metres.

In January 1992, a test field for heat storage in soft clay was completed in Linköping, Sweden. The purpose of the test field was to study energy performance and effects on clay under the influence of high storage temperatures up to 70 °C and alternate freezing/thawing.

Test field design

The store design is based on a vertical duct system which exchanges heat/cold from a circulating fluid. The test field comprises two high temperature heat stores, one store for alternate freezing/thawing and a reference area with no installations. Each store has a volume of 1000 m^3 and is cubic in shape. Single U-shaped ducts, pushed down vertically to a depth of 10 metres with a spacing of 1 metre between the installation points, were installed in the heat stores. In the store for alternate freezing/thawing, the ducts were installed with a spacing of two metres. The pipes were made of reinforced polyethylene (PEX), 25 mm in outer diameter. The top surfaces of the high temperature heat stores were insulated with layers of polystyrene with a foil underneath. The ducts were connected to a conventional

heat supply centre at the site. In this particular research project, electricity was used as the main energy source.

One heat store simulated a seasonal store with varying storage temperature between 35 and 70 °C. Two heating and cooling cycles were performed each year for three years, corresponding to six heating seasons. In the other heat store, the temperature was held constant at 70 °C after the initial heating from natural ground temperature. This procedure made it possible to distinguish effects of temperature variations from effects due to the high temperature alone.

In the store for alternate freezing/thawing, the temperature was varied about the freezing point. Storage temperatures below freezing make it possible to use latent heat released during phase transformation of water in the soil from liquid to solid state.

Equipment was integrated in the stores for measuring temperatures, settlements, horizontal ground movements, pore water pressures and heat flows.

Construction and operation

Results from the construction of the test field and overall operating results show that high temperature storage in soft clay has good prospects of functioning satisfactorily. The ducts were installed with an improved installation method that proved to be cost-effective. Three years of operating the test field provided valuable practical experience, concerning operation as well as field investigations and measurements at high temperatures. Problems with oxygen diffusion through the plastic ducts and related corrosion were rectified by heat exchangers. Part of the measuring equipment showed poor reliablility at elevated temperatures and was replaced. Certain adjustments of the utilised measurement methods were made to compensate for effects of the high temperature.

Results - High temperature storage

Investigations during a period of three years show that the effects on clay of the high temperature are relatively small. The development of settlements in the stores mainly follows the development of temperatures and pore water pressures. Thermal expansion/contraction, mainly of pore water, occurs in connection with temperature increase/decrease. An excess pore pressure is developed during heating, which starts a consolidation process resulting in settlements. The settlements are also affected by creep effects, which start when the temperature increases and the excess pore pressures are equalised.

After six cycles during three years, settlements of the surface of the store with varying temperature measured 72 mm. Total settlements of the store with constant temperature measured 88 mm after 2 years and 8 months of heating. The measured settlements show good agreement with predicted values according to a settlement calculation model developed by Moritz (1995).

The measured changes in most geotechnical properties of the clay were small and mainly within the range of natural variation. The shear strength of the clay appeared to decrease during the initial heating. For the first period of heating this may be explained by an increase in pore water pressure.

Results after three years of operation show small variations in thermal properties of the clay, thermal conductivity and heat capacity. The evaluated heat transfer capacity of the ground heat exchangers is well in agreement with predicted values according to utilised theories and calculation models. The uncertainty of the calculated thermal balance was estimated to be at most 5 %. Measured heat losses showed about 15-25 % higher values than the calculations. Uncertainties may exist in the estimation of additional heat losses between the measuring point in the heat supply centre and the heat stores. Furthermore, calculated values are largely dependent on the boundary temperatures of the heat stores which were estimated using an empirical algorithm. Deterioration of the insulation, both expanded and extruded polystyrene, was observed by an increase in the thermal conductivity of on average 25 %. This was mainly due to water absorption.

Recommendations - High temperature storage

Some recommendations for future applications of ground heat storage in clay can be given based on the results from three years operation of the test field.

With respect to settlements, buildings should be located outside the temperature influenced area around a heat store. In the determination of the safe distance, possible settlement effects outside the area affected by temperature variations must also be considered. Heat stores ought not to be located in slopes where even a moderate decrease in shear strength could initiate instability. In addition, the distance between a heat store and a large building, high road embankment, noise barrier, etc. should be so great that the rise in temperature does not spread and affect the structures or their stability even in the long term.

The surface of a heat store can be used for recreation. It is also possible to use the area for example as a car park, playground or other activities with low requirements on settlements, possibly with some adjustments of the ground surface after the initial phase.

In connection with loading of the surface, particular attention must be paid to the fact that the undrained shear strength may be lowered in order not to jeopardise stability. It should also be borne in mind that the preconsolidation pressure may decrease and/or the creep propensity may increase, which would result in greater deformations than usual in the event of a load being placed on the surface.

The design of heat stores is based on the characteristics of the whole energy supply system and local conditions, especially the geology and the ground water situation. In general, the settlement effects increase with the design storage temperature, and high temperature storage in soft clay therefore requires special attention.

The settlements arise as effects of consolidation and creep. They may be estimated using results from conventional geotechnical laboratory investigations together with a calculation model based on geotechnical properties at elevated temperatures (Moritz 1995). The mean settlement in a heat store in a typical Swedish clay may be calculated in this way. Cyclic fluctuations of the settlements induced by cyclic temperature variations and heave during heating are not included in the model but may be calculated from the coefficients of volume expansion during heating for the soil.

The installed ducts should be separated by heat exchangers from the heat supply system. Otherwise, problems with oxygen diffusion through the plastic ducts must be solved in other ways, for example by proper choice of materials or continuous water treatment.

Results and recommendations for storage around the freezing point

In the store with freeze/thaw cycles, large settlements of about two metres occurred in parts of the store after the initial freezing period in connection with thawing of the clay. To some extent, the deformations were expected because previously unfrozen clay is known to collapse during thawing after an initial period of freezing. However, the deformations caused unexpected buckling of the ducts. Consequently, the operation of the store was terminated after two cycles due to interrupted circulation in the ducts.

Freezing of normally consolidated previously unfrozen soft clay, by extraction of latent heat, is not recommended because large deformations appear in connection with subsequent thawing. Apart from creating other possible problems, the deformations may damage the plastic ducts and thus substantially reduce the function of the store.

Future plans

The test field for high temperature storage will be in operation throughout 1997. The purpose is to investigate heat storage in soft clay at an even higher temperature level, 90 °C, and during a natural decline of the temperature from 35 °C. The performance of high temperature storage in clay should be thoroughly investigated in a full-scale demonstration plant where, for example, costs are more easily verified. Possible investigations for the future also include studies of the behaviour of other types of clay, storage concepts for other geological formations and development of ground heat exchangers. A special task is to investigate the durability of the ground heat exchangers with respect to the settlement process.

Symbols

Units

In general, temperaures are expressed in °C. The heat capacity is expressed in kWh/m^3 °C except in Chapter 6.6 where it is expressed in MJ/m^3 K. Heat quantities are expressed in MWh.

Symbols

A	area
a	thermal diffusivity
B	width of parallelepipedical store
b	thickness
C	volumetric heat capacity
D_i	vertical insulation depth
d_i	insulation thickness
d_p	thermal penetration depth for a periodic temperature variation
H	height of parallelepipedical store
h	heat loss factor
L	length of parallelepipedical store
L_s	characteristic length of the heat store (e.g. height, length or width)
M_o	compression moduli below the preconsolidation pressure σ'_{cTo}
M_{oT}	compression moduli below the preconsolidation pressure σ'_{cT}
M_L	compression moduli for stresses higher than the preconsolidation pressure
n	porosity of soil
$\dot{Q}$	heat supply rate
Q	heat quantity
$\dot{q}$	heat output per length metre
r	radius of sphere

S_r	degree of water saturation
s	settlement
T	temperature
T_m	mean store temperature
T_o	initial store temperature, room temperature
t	time
t_p	periodic time
V	volume
x	distance

Greek symbols

α_s	coefficient of secondary consolidation
ε	relative compression
ε_o	initial relative compression at normal temperature
ε_s	relative compression because of creep
ε_T	relative compression at temperature T
$\Delta\varepsilon_T$	relative compression because of temperature increase and consolidation
λ	thermal conductivity
σ'_c	preconsolidation pressure
σ'_{cT}	preconsolidation pressure at temperature T
σ'_{cTo}	preconsolidation pressure at room temperature T_o
σ'_o	effective vertical stress
τ_{fu}	undrained shear strength

Subscripts

b	boundary
g	grain, ground
gs	ground surface
i	inner, insulation
kl	classified value
o	outer
p	practical value
w	water

Chapter 1.
Introduction

To encourage the use of environment-friendly energy supply applications in the building sector, much attention is given to the potential of solar energy. A seasonal solar energy application must be incorporated with heat storage to bridge the gap between demand and supply of heat and to achieve a high solar fraction at a reasonable cost. The solar fraction is a measure of the available solar heat in relation to the total heat demand. The peak power demand is normally covered by an auxiliary boiler unit. In Sweden, population centres are frequently concentrated to coastal areas and larger watercourses where the geology is dominated by sedimentary soils such as clay, silt, sand or gravel. An interesting solution to the storage problem is seasonal storage in soft clay at high temperatures. The design of such a store is based on a vertical duct system in the clay which exchanges heat/cold by a circulating fluid.

Seasonal heat storage in soft clay has previously been utilised at moderate temperatures of about 30 °C. Unfortunately, the economic competitiveness of seasonal heat storage has often been found to be limited. Higher storage temperatures may increase the technical and economic benefit of heat stores, for instance for solar heat applications. The maximum storage temperature has in the past been limited due to geotechnical concerns and restricted thermal performance of materials involved in the store design. Recently, the quality of the plastic ducts, forming the ground heat exchangers, has been improved. Nowadays, the ducts can withstand higher mechanical forces during the installation process. The material also permits higher operating temperatures and the possibility to reduce diffusion of oxygen and vapour has been improved.

Geotechnical results are available from a number of national plants with heat stores in soft clay. In the town of Söderköping, the heating system for a school and sports hall comprised a seasonal heat store in soft clay (Magnusson et al 1992). The store volume was 36,000 m^3 and the temperature in the store varied between 10 and 30 °C. A similar heat store with a storage volume of 87,000 m^3 was built in the town of Kungsbacka (Gräslund 1986). During 1984, the temperature in the store varied between 9 and 15 °C. In the community of Kullavik, a heat store was built with a subdivision of the store volume into a high temperature zone with a maximum temperature of 50 °C in the centre and a low temperature zone with temperatures between 7 and 20 °C outside this zone (Olsson 1983). The total volume of this store was about 8100 m^3. Temperature effects on clay, heat transfer in the ground and different designs of ground heat exchangers have been studied in a pilot plant close to the town of Kungälv by Adolfsson and Sällfors (1987). Theoretical studies have shown that the economic competiveness of a heat store increases if storage temperatures below the freezing-point are used. The geotechnical impact of freezing in clay has been studied in a heat store for a single house in the village of Utby (Adolfsson et al 1985). The impact of a moderate temperature amplitude (freezing excluded) on the geotechnical properties has proved to be comparatively small and limited to the area of the store itself. The most significant geotechnical results have been total settlements in the order of 0.1-0.2 m. The settlements have affected neither the operation of the stores nor the environment.

From the owner's and user's point of view, a high temperature heat store in soft clay must be proved to function satisfactorily and at a verified and competitive cost. Geotechnical aspects significantly affect both these questions. The storage cost for heat stores in clay has already been shown to be competitive compared to alternative storage concepts. However, there is a need for further reduction of the overall costs of the current heating systems to make a market introduction possible.

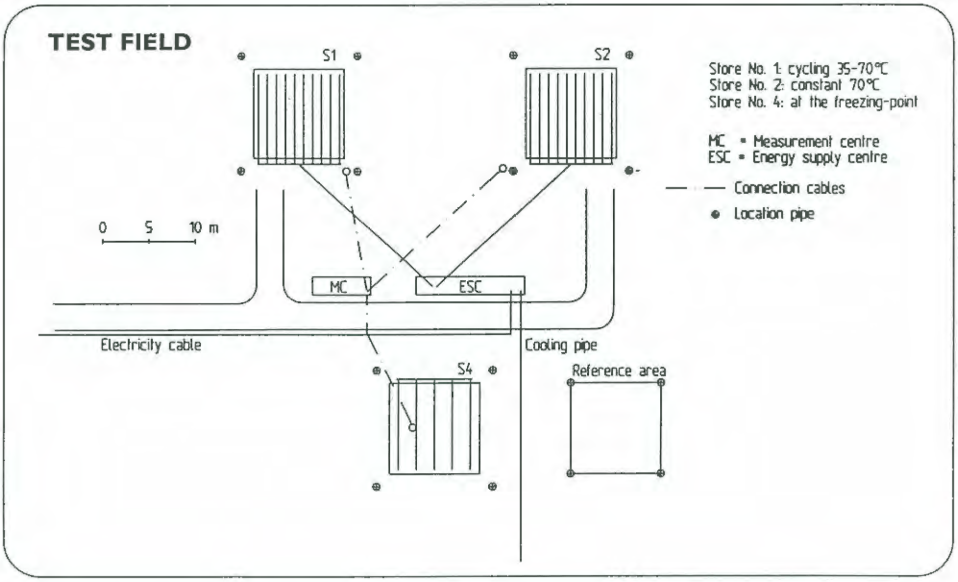
The expected impact of high temperatures in soft clay has previously not been sufficiently well known. Design and construction of heat stores in soft clay require knowledge of geotechnical and thermal behaviour at high temperatures. In the design, questions concerning settlements of the store and the surroundings, temperature spread around the store, changes in strength and deformation parameters, thermal properties and possible reduction of the water content of the clay, ground water movements and degradation of industrial insulation materials are important.

The settlements affect the location of the store with respect to surrounding buildings and other structures, as well as the use of the top surface. Large settlements also exercise an impact on installed ducts and possible couplings in the store. Heat storage involves a certain thermal impact on the soil inside and outside the store, which may result in changes in the geotechnical and thermal properties of the soil. Furthermore, high temperatures and thermal gradients constitute an additional stress on different parts of the heat store construction, for example the insulation. Knowledge of the thermal properties of the clay and the insulation as well as the ground water conditions, is required to design a cost effective heat store and to estimate heat losses. A cost effective heat store design is based on an optimisation of the investment costs in relation to the heat transfer capacity (number and shape of installed ground heat exchangers) within the heat store and the heat losses. Furthermore, construction and operation experience is necessary to demonstrate agreement between calculated and actual costs in order to form a relevant basis for decisions by prospective investors and consumers.

Another possible economical seasonal heat storage application is an energy supply system based on combined heat and cold storage utilising the phase transformation heat with the aid of a cooling machine/heat pump. In principle, excess heat in buildings is replaced by comfort cold from the store during the summer. In winter, the operating mode is inverted. The use of latent heat makes it possible to design a compact store. The low investment cost and the extended operation time create good economic conditions. An important geotechnical restriction is large expected settlements, especially in connection with the first thawing cycle of soft clay.

Chapter 2.

Objective and methods



In order to address some of the questions in Chapter 1, it was decided to study high temperature storage in clay in a pilot plant. In January 1992, a test field for heat storage in soft clay was completed in Linköping, Sweden. The test field was largely designed and constructed by the Swedish Geotechnical Institute (SGI) with funds from the Swedish Council for Building Research (BFR). Costs for research activities were shared between the BFR and the SGI.

The purpose of the test field was to study energy performance and effects on clay under the influence of a high store temperature, 70 °C, and alternate freezing/thawing. In addition to gaining practical experience of heat store construction and studying overall energy performance, a research programme was formulated and divided into four major parts. The following aspects have been studied in particular:

- Thermal impact on the geotechnical behaviour of the clay
- Thermal properties of the clay
- Thermal performance of the insulation
- Heat transfer capacity of the ground heat exchangers

The investigations of heat storage were performed at a constant high storage temperature of 70 °C, with a fluctuation of the temperature between 35 and 70 °C and around the freezing point, respectively. Thorough cost analyses are less relevant for a small pilot plant designed for scientific purposes. Therefore only minor studies of the costs have been performed in this project.

Investigations and measurements in the field were scheduled for a period of three years. The thermal impact in the ground has been investigated in the centre of the store, at the edge of the store and at specific distances from the store. Natural variations of settlements and pore water pressures were followed in a reference area. Installed equipment and methods of measurement and investigation are described in detail in Chapter 5.

Apart from activities related to the specific research programme, extensive monitoring work was undertaken to evaluate the thermal balances of the heat stores. Part of the monitoring work included readings of temperatures, energy transferred by the heat carrier fluid and fluid flow.

2.1 TEMPERATURE EFFECTS ON THE GEOTECHNICAL BEHAVIOUR OF CLAY

A high storage temperature will influence the geotechnical properties of the clay. Changes in the geotechnical properties of the soil are significant when estimating settlements in heat stores and how near to surrounding buildings a heat store can be located without causing damage due to the expected settlements. Settlements of heat stores affect the use of the ground area and possibly the function of the stores. Special attention should also be given to possible changes in shear strength.

> The objective was to investigate the development of settlements at high temperatures in clay and the temperature effects on geotechnical properties, in particular the shear strength of clay.

The settlement processes at high temperatures and in freezing and thawing of clay were investigated in the test field. An understanding of how the settlements arise is required to enable a translation of the results from the test field to other areas being considered for heat storage. The monitoring of pore water pressure is of great importance in explaining the settlement process and the development of settlements both within the store and at certain distances from the store. Settlements as well as the pore water pressure were closely followed in the test field. The pore water pressure was assumed to be related to the temperature and the temperature was measured in connection with the pore water pressure readings. The investigations also included laboratory examination of extracted soil samples. The shear strength of the clay was investigated both in the field and in the laboratory. The obtained results were compared to results from investigations prior to the construction of the test field.

2.2 THERMAL PROPERTIES OF CLAY AT HIGH TEMPERATURES

Thermal properties of soil and rock at normal temperatures are well known. Thermal conductivity is an important parameter in the design of heat stores and the estimation of heat losses. If a relevant value for the particular soil and conditions can be found, costs can be reduced through more accurate design.

Heat transfer by conduction dominates at moderate temperatures, below 25-30 °C. At higher temperatures, vapour diffusion contributes to the heat transmission in unsaturated conditions in soils. Vapour diffusion may cause a certain drying effect of the upper parts of a store and thereby reduce the performance of the store.

The objective was to determine the thermal properties at high temperatures and investigate whether possible vapour diffusion leads to drying of the ground heat store.

The thermal conductivity of a soil may be approximated by the aggregate effects of the thermal conductivity of its constituents; soil particles, pore water and pore gas. The thermal conductivty of water and pore gas is known to increase with increasing temperature, whereas the effect of the temperature on the soil particles is less certain. Changes in mainly porosity and water content of the soil affect the thermal properties. The thermal conductivity of the clay was evaluated in the heat store with constant storage temperature, about 70 °C. In addition, possible drying of the clay was estimated from laboratory investigations of soil samples.

2.3 THERMAL PERFORMANCE OF THE INSULATION

Practical experience of the performance of the insulation from high temperature storage applications in the ground is very limited. Generally, the thermal conductivity of the insulation is given by the manufacturer as an idealised theoretical value. In practice, a conservative value of 0.05 W/m°C is often used. If a relevant value for the thermal conductivity can be determined more carefully, it would lead to an optimal design. The insulation is chosen with consideration to the insulation costs in relation to costs for heat losses.

The objective was to investigate the capability of the insulation material to retain a low thermal conductivity at high temperatures and moist conditions.

It was decided to investigate the thermal performance of two different compositions of insulation based on extruded (XPS) and expanded (EPS) insulation respectively. Extruded polystyrene may be considered better than expanded polystyrene with respect to given values for thermal performance. Another important difference between the insulation materials is the price, the cost of expanded polystyrene being about half that of extruded polystyrene.

The change in thermal conductivity of the insulation depends mainly on moisture absorption and on ageing in the case of extruded polystyrene, i.e. replacement of insulating propellant gas (HCFC) by air. Both processes increase the thermal conductivity. It may be noted that this particular extruded polystyrene is nowadays manufactured with pure air as insulating propellant gas. The extruded polystyrene is relatively homogenous with closed cells, whereas the structure of expanded polystyrene is more open with air-filled cells. This difference in cell structure results in higher water absorption and lower density for the expanded polystyrene. Furthermore, the insulation may be supplemented with a vapour protective foil. Metal based vapour protection foils are more resistant to vapour diffusion than an ordinary plastic foil.

Measurements of the thermal conductivity of the insulation were performed in the heat store with constant storage temperature of about 70 °C. Compared to the heat store with cyclic temperature, the following observations are made:

- The temperature gradient in relation to the surroundings is always the highest possible.
- Mechanisms behind moisture movements are more pronounced.

- A higher temperature level has a stronger effect on the insulating capacity.
- A high temperature may reduce the compressive strength.

The studies of the thermal performance of the insulation also included investigations of the water content of the insulation and the soil close to the insulation.

2.4 HEAT TRANSFER CAPACITY OF THE GROUND HEAT EXCHANGERS

Heat stores in clay are normally constructed by installing vertical U-shaped plastic ducts. Each U-shaped duct constitutes a ground heat exchanger (GHE). Heat or cold is exchanged to the store soil volume from a circulating fluid in the duct system. The heat transfer capacity of the ground heat exchangers is an important parameter in the design of heat stores. The capacity of the heat store is proportional to the number of ground heat exchangers in the store and the heat transfer capacity of each individual duct. The design is based on computer simulations, where the number of ground heat exchangers is calculated from material properties and the configuration of the ground heat exchangers, thermal properties of the ground, thermal resistance between the fluid and the ground, and temperature and geometry of the store.

The objective of this subtask was to determine the heat transfer capacity of the ground heat exchangers in the field at high storage temperatures.

The heat transfer capacity of a store was estimated by performing a thermal response test. By comparing the result from the test with the result of theoretical calculations, the model for the thermal performance of the ground heat exchangers may be verified. Provided that the theory is correct and describes the process of heat transfer sufficiently well, future heat stores in clay can be designed more accurately and probably result in lower costs.

Thermal response tests are performed by supplying heat at a constant heat injection rate for approximately one week and measuring the response in the fluid temperature. Prior to the test, the fluid is circulated in the ducts with no heat supply/extraction in order to reduce temperature gradients in the store. To check the temperature dependence of the heat transfer capacity, response tests were carried out in the heat store with cyclic temperature at two temperature levels, 35 and 60 °C respectively.

Chapter 3.

Theoretical outline

3.1 SETTLEMENTS IN CONNECTION WITH HEATING

General

The process of heave and settlements in the stores upon an increase in temperature is initially caused by a volumetric expansion of the soil during heating and an associated development of pore pressure. The amount of heave and the development of pore pressure is governed by the size of the temperature change and the rate at what it takes place. The effects have a tendency to decrease with the number of temperature cycles and time. The increase in pore pressure starts a consolidation process during which settlements develop. The settlements are also affected by creep effects in the soil. The total vertical relative compression, ε , in a heat store can be expressed as

$$\varepsilon = \Delta\varepsilon_T + \varepsilon_s \qquad (3.1)$$

where $\Delta\varepsilon_T$ is the relative compression caused by a rise in the temperature and the subsequent consolidation process, and ε_S is the relative compression due to creep effects.

Consolidation settlements

When the temperature in the store increases, the soil volume will expand due to thermal expansion of soil particles and pore water. An excess pore pressure is built up partly due to the difference between the thermal expansion properties of the soil particles and water and to some extent also because of the ground resistance to horizontal expansion. The pore pressure increases as long as the rate of temperature increase is high and the drainage possibility is limited. The magnitude of the increase in pore pressure is also dependent on the type of soil and the stress situation in the soil.

Where an excess pore pressure exists, the soil starts to consolidate and the excess pore pressure dissipates. The rate of the consolidation process depends on the draining conditions. The development of excess pore pressure follows the temperature, increasing during energy charge and decreasing during discharge, which will also be reflected in the development of the deformations. Heave and settlement are deformations caused by the volume of pore water and clay particles increasing and decreasing as a result of the temperature fluctuations. The magnitude of the amplitude depends on the temperature changes, the heat injection/extraction rate and drainage conditions in the soil. When excess pore pressure prevails, it is assumed that no significant creep settlements occur.

When the heat store cools and the temperature decreases, the soil volume will decrease because of thermal contraction of pore water and soil particles. This will result in increasing settlements. Thermal contraction of the pore water will cause a reduction in pore pressure. When a heat store is actively cooled, a negative excess pore pressure may occur. This negative excess pore pressure arises if free water is not available to be sucked up at the same rate as the cooling and shrinking process proceeds. Negative excess pore pressures theoretically give rise to corresponding effective stress increases, which in turn are governed by the compression modulus of the soil.

Creep settlements

Creep is also referred to as secondary consolidation. It is time-dependent and normally takes place so slowly that no hydraulic gradient arises. The process of creep normally starts when the stresses are about 80 % of the preconsolidation pressure. The preconsolidation pressure is a yield stress at which consolidation settlements start. Creep settlement is calculated from the relation

$$\varepsilon_s = \alpha_s \cdot \log\frac{t_1}{t_2} \qquad (3.2)$$

where α_s is the creep parameter and the time $t_1 > t_2$. The creep parameter α_s is also referred to as the coefficient of secondary consolidation.

Larsson (1986) has shown that the creep parameter α_s is dependent on the deformation as shown in *Figure 3.1*. Early on, α_s has a very low value, which at a certain deformation starts to rise rapidly to a maximum ($\alpha_{s,max}$) and then declines slowly with increasing compression. The magnitude of α_s has proved to vary with the water content and to a certain extent also with the type of soil.

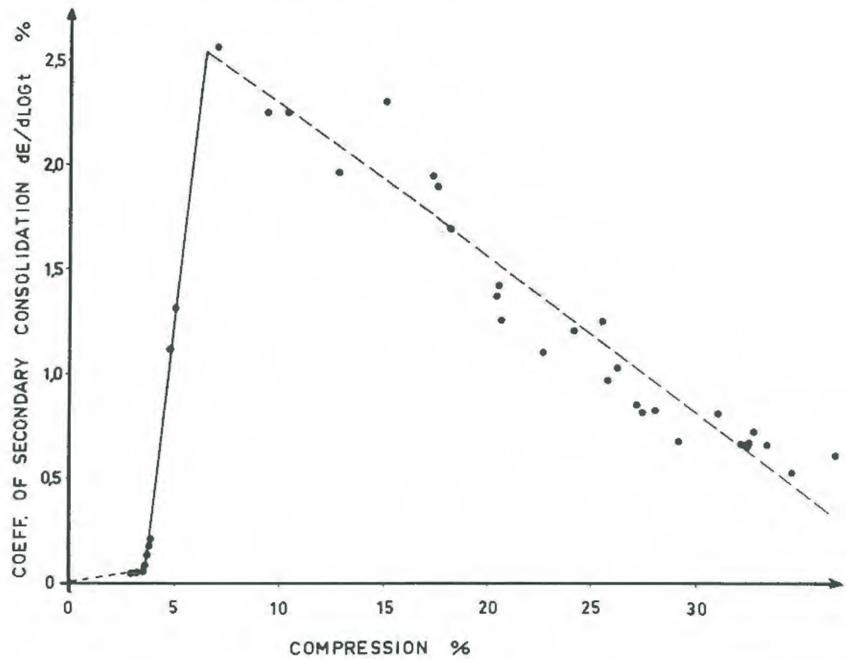


Figure 3.1 Coefficient of secondary consolidation, α_s, versus relative compression for Bäckebol clay, Larsson (1986).

For a soil profile divided into n number of layers, the settlement s is obtained by adding the relative compression times the thickness b for each layer according to

$$s = \sum_{1}^{n} \varepsilon_n \cdot b_n \qquad [\text{m}] \qquad (3.3)$$

Temperature dependence

According to the observations and results reported by Moritz (1995), the settlement in a heat store can be estimated by using a preliminary calculation model. In the model, it is assumed that the temperature is the only load effect. Should the effect of some other load, for example in the form of fill on top of the heat store, come into play, a more complex problem would arise. The calculation model is based on the assumption that the preconsolidation pressure decreases as the temperature increases. Alternatively, this may be expressed as a creep process starting at a lower effective stress level at elevated temperatures than at normal temperatures.

In order to use the model to calculate the settlements in a heat store, the temperature in the middle of the store during operation must be known. An estimation must be made of the duration of excess pore pressures in every temperature cycle. The deformation parameters are evaluated from CRS oedometer tests performed according to Swedish standard and at normal temperatures. Subsequently, new "preconsolidation pressures" for the elevated temperatures must be calculated as well as new compression moduli, M_{oT}. The in situ vertical effective stress is calculated and compared with the original preconsolidation pressure and the calculated preconsolidation pressure at the elevated temperature.

From laboratory results performed at different temperatures, an empirical relation between the preconsolidation pressure at normal temperature conditions and the preconsolidation pressure at elevated temperatures has been found. The preconsolidation pressure, σ'_{cT}, at a certain temperature T can be expressed as

$$\sigma'_{cT} = \sigma'_{cT_o}\left(\frac{T_o}{T}\right)^{0.15} \qquad \text{[kPa]} \qquad (3.4)$$

where σ'_{cTo} is the measured preconsolidation pressure at room temperature and T_o is the corresponding room temperature in °C. The equation describes a non-linear decrease of the evaluated preconsolidation pressure with rising temperature for this type of clay.

The modulus at effective stresses below the preconsolidation pressure, M_0, is a constant modulus applicable up to the preconsolidation pressure. M_0 is generally described as an elastic modulus. According to empirical relations, M_0 can be evaluated on the basis of the preconsolidation pressure in accordance with $M_0 \approx 50 \cdot \sigma'_c$ or on the basis of undrained shear strength, τ_{fu}, in accordance with $M_0 \approx 250 \cdot \tau_{fu}$ (applicable to highly plastic clays) (Larsson et al 1994). The compression modulus, M_{oT}, below the preconsolidation pressure σ'_{cT} at temperature T can empirically be expressed as

$$M_{oT} = M_o(1 - 0.005 \cdot \Delta T) \qquad \text{[kPa]} \qquad (3.5)$$

where M_o is the compression modulus at stresses lower than the preconsolidation pressure and T is the difference in temperature between the temperature T and the temperature prevailing when M_0 was measured [°C]. Normally, M_0 is determined at room temperature.

For effective stresses higher than the preconsolidation pressure, the compression modulus M_L is used. Results from laboratory tests performed by Moritz (1995) show that the measured values of the compression modulus M_L appear to be independent of temperature changes.

As long as the vertical stress is on the elastic part of the curve ($<\sigma'_{cT}$), the excess pore pressure will be equalised relatively quickly since the compression modulus is high. The additional compression, $\Delta\varepsilon_T$, which is caused by the rise in temperature and subsequent consolidation can be expressed as

$$\Delta\varepsilon_T = \varepsilon_T - \varepsilon_o \tag{3.6}$$

where ε_T is the relative compression at temperature T [°C], and ε_0 is the initial relative compression at normal temperature for the same stress. For $\sigma'_0 \leq \sigma'_{cT}$, the equation can be expressed in stresses and moduli as

$$\Delta\varepsilon_T = \frac{\sigma'_o}{M_{oT}} - \frac{\sigma'_o}{M_o} \tag{3.7}$$

If $\sigma'_0 > \sigma'_{cT}$, the expression becomes

$$\Delta\varepsilon_T = \frac{\sigma'_o}{M_{oT}} - \frac{\sigma'_o}{M_o} + \left(\frac{\sigma'_o - \sigma'_{cT}}{M_L}\right) \tag{3.8}$$

and the equation in stresses and moduli for this case is illustrated in *Figure 3.2.*

The creep settlement according to equation (3.2) is added to this consolidation settlement. During the period of time that an excess pore pressure prevails, it is assumed that no creep occurs. Creep is assumed to start at a vertical stress $\geq 0.8\ \sigma'_{cT}$ and attain its maximum at the preconsolidation pressure.

By combining equations (3.2) with (3.7) and (3.8) respectively, the total deformation for $\sigma'_0 \leq \sigma'_{cT}$ can be expressed as

$$\varepsilon = \frac{\sigma'_o}{M_{oT}} - \frac{\sigma'_o}{M_o} + \alpha_s \cdot \log\frac{t_1}{t_2} \tag{3.9}$$

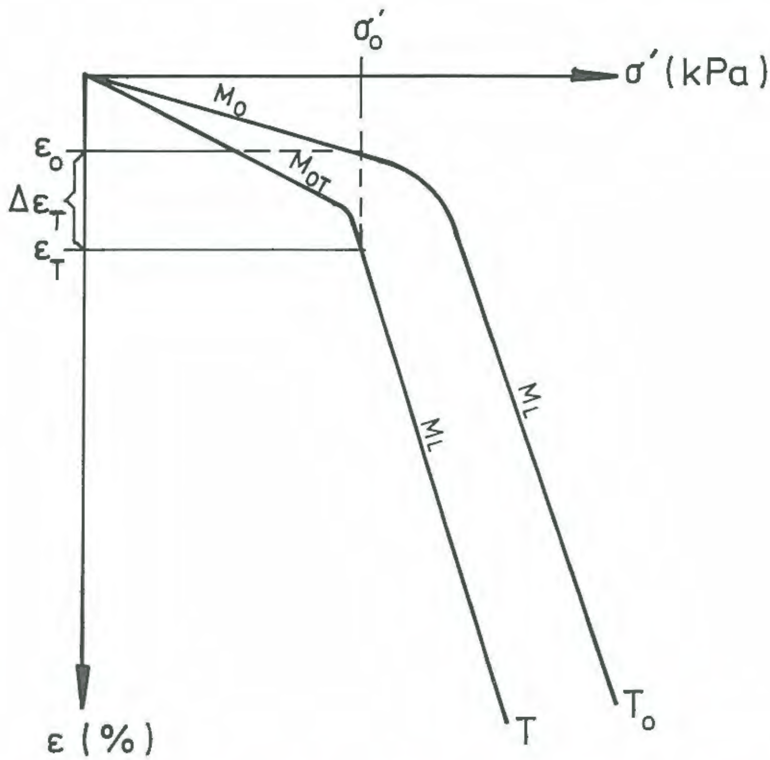


Figure 3.2 Stress-deformation curves for temperatures T_o and T.

and for $\sigma'_o > \sigma'_{cT}$ as

$$\varepsilon = \frac{\sigma'_{cT}}{M_{oT}} - \frac{\sigma'_o}{M_o} + \left(\frac{\sigma'_{cT} - \sigma'_o}{M_L} \right) + \alpha_s \cdot \log \frac{t_1}{t_2} \qquad (3.10)$$

The next step is to determine the value of the creep parameter, α_s, which depends on the water ratio and type of soil. The maximum value of the creep parameter, $\alpha_{s,max}$, together with the inclination $\beta_{\alpha s}$ for the remaining part of the curve in Figure 3.1 can be estimated from Larsson et al (1994). Based on the assumption that creep starts at the stress level of 0.8 σ'_{cT}, the creep parameter α_s for any effective vertical pressure can be calculated. For a heat store with cyclic temperature variation, time t_1 is approximated with the period of time during which creep occurs and time t_2 is approximated with the length of time until creep starts.

Calculated settlements

Calculations of the settlements were made for the heat store with a constant temperature of 70 °C and the heat store with temperature varying between 35 and 70 °C in two cycles per year, *Table 3.1*. The clay is assumed to consist of a single homogenous layer and the calculation model gives only approximate values.

Table 3.1 Calculated settlements in metres for the heat store with constant temperature of 70 °C and the heat store with varying temperature after three years of operation.

	T constant 70 °C	T varying 35-70 °C
Consolidation settlement ($\Delta\varepsilon_T$)	0.030	0.030
Creep settlement (ε_S)	0.054	0.036
Total settlement (ε)	**0.084**	**0.066**

The model does not include heave due to heat expansion of pore water and soil particles. Neither does it account for variations in the settlement process which in reality take place because of fluctuations in the temperature. An outline of the development of mean and real settlements in a heat store when the temperature fluctuates is shown in *Figure 3.3*.

The creep effect will decrease when the heat supply is diminished. The magnitude of the creep settlement depends on the stress situation and the water content of the soil. For a heat store the creep settlement may be greater than the consolidation settlement in the long term.

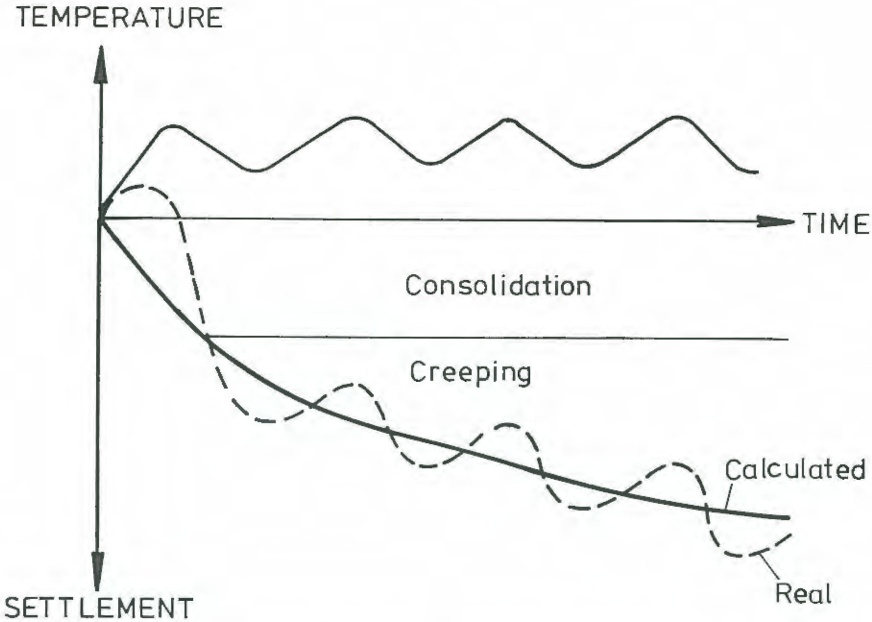


Figure 3.3 Outline development of the settlements in a heat store with varying temperatures. Settlements due to a consolidation process dominate at the beginning, while settlements due to creep effects often increase in importance with time.

3.2 SETTLEMENTS IN CONNECTION WITH FREEZING

Freezing of the soil will cause an expansion of the soil volume as the pore water is gradually converted to ice (Adolfsson et al 1985). The degree of expansion is primarily dependent on the water content of the soil. In a fine grained soil, some of the pore water will still remain unfrozen even if the temperature is reduced below 0 °C. The share of unfrozen pore water will decrease with decreasing temperature. Regardless of whether bonds between mineral particles and adjacent pore water on the microscale remain intact or not, freezing of the soil will result in a collapse of the soil structure in connection with thawing. In cohesive soils with high void ratios, this destruction will result in large settlements.

In the store with alternate freezing/thawing, settlements were expected to occur in the frozen and subsequently thawing parts of the soil. The soil around each vertical ground heat exchanger was expected to freeze, see *Figure 3.4*. Frozen pillars of previously unfrozen soil, 10 metres in length, would develop. The radius of the pillars was calculated by using a theory for steady-state heat conduction. Freezing for three months with an output of 5 kW would result in a mean freezing diameter

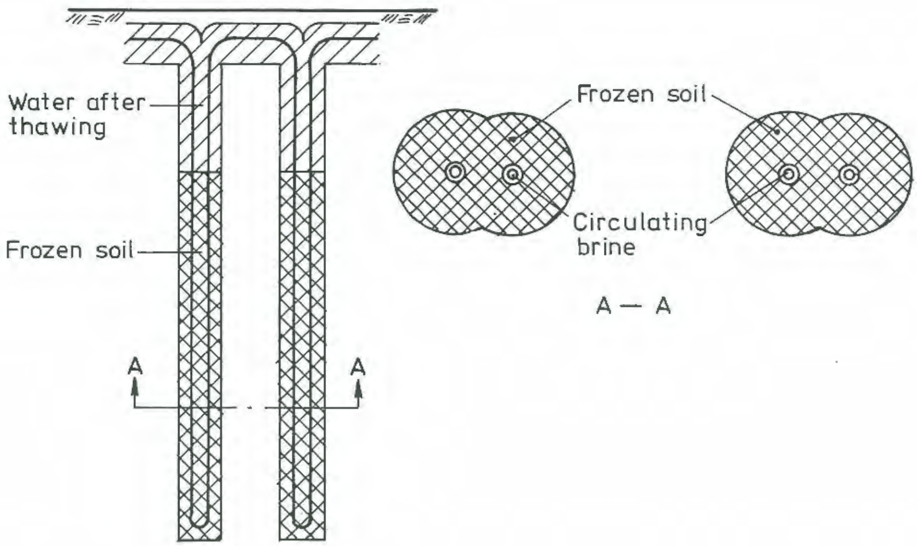


Figure 3.4 Outline of predicted frozen parts of soil around the vertical ground heat exchangers.

of about 0.3 metre around a vertical plastic pipe with an outer diameter of 25 mm, in clay.

Thawing of frozen soil that has never been frozen before results in water separation. Pore water separated from the soil volume in connection with thawing was expected to gather at the upper part of the pillars and the thawed soil in the lower parts. Possibly, the settlements of the thawed clay would not significantly affect the unfrozen parts between the duct loops, leaving that soil fairly intact.

In order to predict the settlements of the thawed clay in the store, investigations presented in the literature were used. Investigations in the laboratory (Vähäaho 1989) indicate that the volumetric deformations in previously unfrozen pure clay will be about 25 %. In the present case this would mean 2.5 metre deep hollows with a total diameter of about 0.6 metre around each vertical U-shaped ground heat exchanger. The hollows would be filled with water.

3.3 RANGE OF TEMPERATURE DISTURBANCE

General

Heat will be transferred to the surroundings of the heat stores. An increase in temperature may affect the thermal and geotechnical properties of the soil and the development of settlements inside as well as outside the heat store. This emphasises the importance of estimating the extension of the thermal influence outside a heat store. However, it is not easy to determine the extent to which the temperature can increase without causing additional settlements.

The thermal extension from a plane surface with a periodic temperature variation can be estimated for a one-dimensional and semi-infinite case. The temperature T at a distance x from the side of the store at time t is given by (Carslaw and Jaeger 1959)

$$T(x,t) = T_1 \cdot e^{-x/d_p} \cdot \sin(2\pi \cdot t/t_p - x/d_p) \quad [°C] \qquad (3.11)$$

$$d_p = \sqrt{a \cdot t_p / \pi} \quad [m] \qquad (3.12)$$

where T_1 is the amplitude of the sinusoidal temperature variation at x = 0 and t_p is the periodic time of the temperature variation. d_p is the thermal penetration depth for the periodic variation and a is the thermal diffusivity. After some mathematical transformation, the equation is simplified to

$$|T| = |\hat{T}_1| \cdot e^{-x/d_p} \quad [°C] \qquad (3.13)$$

Thus the amplitude of the temperature is subdued by a factor e^{-x/d_p} with increasing distance from the store. For example, at distance d_p the amplitude has diminished to e^{-1} (0.37) of the amplitude of T_1.

Calculated range of temperature disturbance

The heat stores are situated close to the ground surface and extend to a limited depth. Hence the effect of a sinusoidal variation of the temperature at the ground surface as well as at the side of the store has to be considered in the calculation. The temperature influence at moderate distances from the heat stores was calculated with the aid of a special computer programme written by Göran Hellström at Lund University of Technology.

The programme calculates the temperature at a specific point outside the store, after a certain period of operation, based on the mean store temperature at the side of the store, the seasonal temperature variation at the ground surface and the thermal properties of the ground. First, the initial ground temperature is calculated for a mesh covering the ground outside the store, based on the surface temperature according to the theory of temperature spread from a plane surface (as above). The temperature may then be expressed as a specific enthalpy for each cell. Heat flow from the store and the ground surface gives rise to changes in specific enthalpy in the ground. The change in specific enthalpy, from one day to another, corresponds to a rise in temperature which is calculated.

The programme may be used for distances where the boundary effects are negligible, approximately for distances less than the length of the side of the store. For greater distances the effect of a limited side area of the store has to be considered.

The temperature after three years of operation was calculated at distances corresponding to where the temperature was measured; 1, 4 and 7 metres outside heat store No. 1 and 2 metres outside heat store No. 2. The distance from the outer duct to the edge of the store is defined as half the spacing between the ground heat exchangers, 0.5 metre. Estimated mean store temperatures (Chapter 5.6) based on measurements in the stores were used for the calculations. The calculated temperature at 6 metres depth, 1, 4 and 7 metres outside heat store No. 1 reaches at the most 45, 24 and 15 °C, respectively, *Figure 3.5*. The corresponding value 2 metres outside heat store No. 2 was calculated at approximately 48 °C.

The mean temperature at the side of the store was set equal to the mean store temperature. Normally, the mean temperature at the side is somewhat lower than the mean temperature for the whole store volume, which means that the calculated temperature spread is somewhat overestimated. The thermal diffusivity of the soil was estimated at $2.9 \cdot 10^{-7}$ m^2/s based on mean values of obtained thermal properties of the specific soil.

In order to estimate the thermal influence at greater distances around the heat store, a more complex tool was used. The DST model (Duct ground heat STorage model) calculates the temperature field around a cylindrical ground heat store with a vertical symmetry axis (Hellström 1989:2). Heat is transferred to the ground by conduction from a circulating liquid in a system of ground heat exchangers which are uniformly placed within the storage volume. Any type of insulation of the store (vertical/horizontal) may be specified.

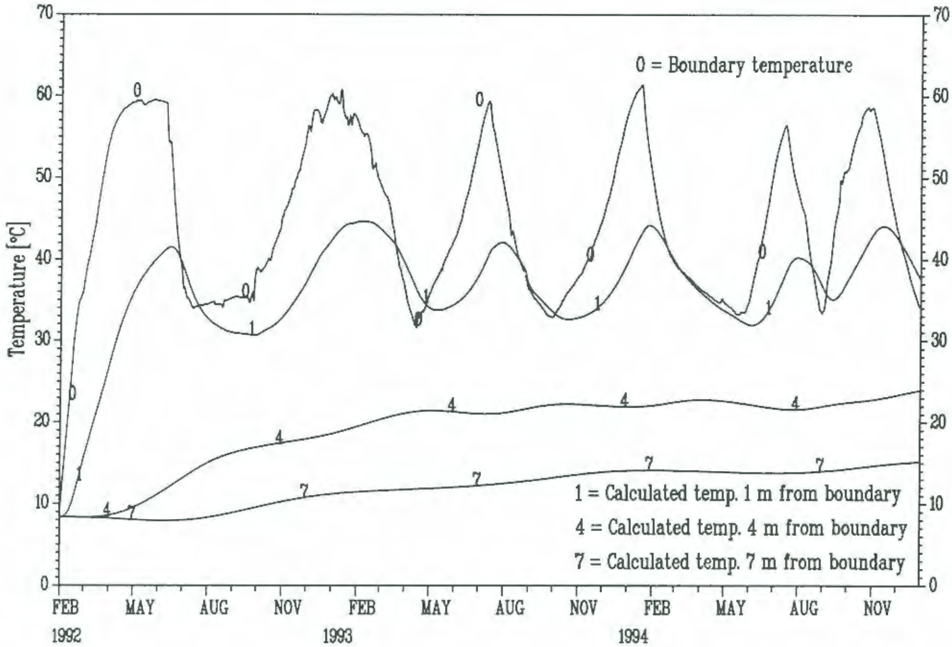


Figure 3.5 Calculated temperatures at various distances outside store No. 1 (6 m depth). The boundary temperature was estimated from measurements.

In the model, the temperature in the ground is represented by three parts; a global temperature, a local solution and a steady-flux part. The global problem covers the large-scale thermal process between the store and the surrounding ground, different parts within the storage volume and the influence of conditions at the ground surface etc. Details in the temperature field associated with individual ducts are left to the local problem and the steady-flux part.

The temperature field was calculated for a two-dimensional mesh with a radial coordinate and a vertical coordinate covering the storage region and an area outside the store. The calculated range of a temperature disturbance based on actual loading conditions is presented in *Table 3.2*. The heat store was expected to cause a small temperature disturbance (0.1 °C) about 23.0 metres from the centre of the store after six cycles during 2 years and 11 months. The same temperature disturbance is estimated at 22.8 metres from the centre of the store with constant temperature after 2 years and 8 months of operation.

Table 3.2 Calculated range of the temperature disturbance (0.1 °C), from the centre of the store at a depth of 6 metres, after each temperature cycle 35-70 °C.

Cycle No.	Number of days	Mean store temperature [°C]	Range of temp. disturbance [m]
1	210	45	15.5
2	227	48	16.2
3	168	43	18.1
4	213	43	17.6
5	123	42	18.7
6	121	47	23.0

For comparison, the temperature spread for a full-scale store of 15,000 m^3, 15 metres in depth with a cyclic inlet fluid temperature between 35 and 75 °C, is calculated at about 30 metres outside the edge of the store after 25 years of operation. The calculation was made with a simplification of the loading conditions by assuming intermittent changes of the fluid temperature.

3.4 HEAT LOSSES

General

The heat losses from a seasonal ground heat store operated at elevated temperatures are a dominant part of the thermal heat balance of an energy supply system. The heat losses not only influence the operating cost but also the investment cost. Much attention was therefore given to the possibility of reducing the economic impact of the heat losses in the initial design study and also to monitor the thermal heat losses in the test field.

Heat transport in the ground mainly takes place by conduction. The global thermal heat losses of a heat store consist of three components. There is a steady-state part, a periodic variation during an annual cycle and an initial part with transient thermal build-up of the temperature field around the store (Hellström 1991). The heat flow through the boundaries of the store determines the heat losses. The net heat flow of the periodic component becomes zero for an annual cycle. The build-up of the temperature field around the store may be important during the first 2-10 years of operation. The larger the heat store, the longer the duration of the transient process. The transient process gradually approaches a time independent steady-state condition.

The seasonal temperature variations may be important for the distribution of heat losses during the cycle, but they do not influence the annual heat losses. The heat losses are therefore determined by using the average store temperature during the annual cycle.

The heat flow ($d\dot{Q}$) through an arbitrary area (dA) at steady-state temperature distribution is defined as

$$d\dot{Q} = -\lambda \cdot dA \cdot dT/dn \qquad \text{[W]} \qquad (3.14)$$

where dT/dn is the temperature gradient in the normal direction of dA and λ is the thermal conductivity. The negative sign in the formula indicates transfer of heat from a high to a low temperature level.

If the thermal conductivity is constant over the area and the temperature gradient in the normal direction of the area is constant, an integration of the formula gives

$$\frac{\dot{Q}}{A} = -\lambda \cdot \frac{dT}{dn} \qquad [\text{W/m}^2] \qquad (3.15)$$

Consider a plane boundary with thickness b and a hollow sphere with inner and outer radius r_i and r_o, respectively. The heat transfer is maintained in the direction from the inner to the outer surface temperature, where $T_i > T_o$. After integration, the formulas for heat flow are expressed as

$$\dot{Q} = A \cdot \lambda \cdot (T_i - T_o)/b \qquad \text{(plane surface)} \qquad (3.16)$$

$$\dot{Q} = 4 \cdot \pi \cdot \lambda \cdot (T_i - T_o)/(1/r_i - 1/r_o) \qquad \text{(hollow sphere)} \qquad (3.17)$$

Thus, the heat loss is proportional to the temperature difference between the inner and the outer boundary and the thermal conductivity of the ground.

For a heat store application, the heat loss is obtained by calculating the three-dimensional steady state temperature field. T_i represents the boundary temperature of the store, T_b, and T_o the mean temperature at the ground surface, T_{gs}. The boundary temperature is normally assumed to be equal to the mean store temperature. A reasonable estimation of T_{gs} is the mean temperature of the ambient air.

Calculated steady-state heat losses

The steady-state heat loss between the surface of the heat store and the ground surface is expressed as (Hellström 1991)

$$\dot{Q} = \lambda_g \cdot \left(T_b - T_{gs}\right) \cdot L_s \cdot h \qquad \text{[W]} \qquad (3.18)$$

where L_s is defined as a characteristic length of the heat store. It is possible to use the vertical extension or some horizontal width of the store. By scaling with the length, L_s, a dimensionless description of the heat store is obtained. The dimensionless heat loss factor, *h*, is a function of scaled lengths, i.e. the shape and position of the store.

The geometry of the monitored heat stores is characterised by storage depth, length and width (*H*, *L* and *B*) forming a cubic shape of 1000 m^3 and an ambient area of 600 m^2. The upper boundary of the heat store coincides with the ground surface. The entire upper boundary and the upper part of the vertical sides (three sides out of four) are thermally insulated. The thermal insulation is defined by the thickness (d_i), the thermal conductivity (λ_i) and the depth of the vertical insulation (D_i). The thermal property of the ground is defined by the thermal conductivity (λ_g).

During the monitoring period, between February 1992 and December 1994, the temperatures in the ground and the air have been registered continuously and the thermal conductivity has been estimated from laboratory analyses of clay samples. The boundary temperatures of the heat stores were approximated with the mean store temperatures for the later part of the monitoring period when steady-state conditions applied (Chapter 5.6).

H, L, B = 10 m	d_i = 0.2 m
λ_g = 1.03 W/m°C	λ_i = 0.04 W/m°C
T_{gs} = 7.5 °C	D_i = 1 m
T_b = 46 °C (heat store No. 1)	T_b = 68 °C (heat store No. 2)

The steady-state heat losses from the heat stores may be estimated by an analytical solution of a parallelepipedical insulated geometry with the upper boundary at the ground surface, *Figure 3.6.*

For a heat store similar to the monitored heat stores in the test field, the total steady-state heat loss may be expressed as (Hellström 1991)

$$\dot{Q}=\left(T_b-T_{gs}\right)\cdot\left\{\left(\lambda_g\cdot H\cdot h\right)+\left(\lambda_i/d_i\right)\cdot\left(L\cdot B+\left(L+B\right)\cdot D_i\right)\right\} \text{ [W]} \qquad (3.19)$$

The dimensionless heat loss factor, h, is obtained from the calculation of heat

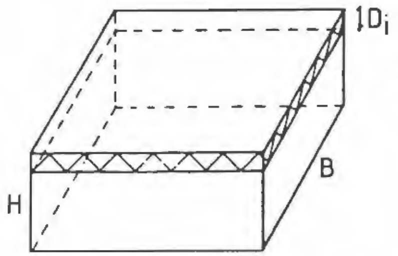


Figure 3.6 Parallelepipedical storage volume at the ground surface. The upper boundary and the upper part of the vertical side are thermally insulated (Hellström 1991).

losses from the uninsulated part of the store. The heat loss factor is determined from the steady-state temperature field in the ground around the store, in this case, by scaling with the vertical extension of the store, H. For the current shape and position of the heat stores (L/H=1, B/H=1, D_i/H=0.1), the heat loss factor is estimated at 12.2 (Hellström 1991).

h = 12.2

The steady-state heat losses are calculated at 5.8 kW for heat store No. 1 and 9.1 kW for heat store No. 2, using equation 3.19.

Chapter 4.

Design and construction of the test field

4.1 TEST SITE

The test field for high temperature storage and alternate freezing/thawing is located near the marina in Linköping, a city located about 200 km south-west of Stockholm. The area is covered with grass and is situated adjacent to the Stångån river where it flows into Lake Roxen. The Swedish Geotechnical Institute has performed CPT tests, field vane tests and standard piston sampling in which undisturbed soil specimens from 12 different levels were extracted. The results of the field tests and laboratory examinations of the extracted specimens are described in detail by Bergenståhl et al (1990).

The ground at the site, *Figure 4.1*, mainly consists of soft and fairly homogenous clay to a depth of 18 metres. A two metre layer of dry crust at the top lies on clay with plant remnants which changes to normal clay after another 2 metres. Below 8 metres depth sulphidic stains appear in the clay down to 11-12 metres. Deeper layers contain thin layers of silt down to a dense bottom layer about 18 metres below the ground surface.

The water content in the clay below the dry crust mainly varies between 70 and 85 % of dry weight. The undrained shear strength increases with depth from approximately 17 kPa at 4 metres depth to 20 kPa at 11 metres. CRS tests previously carried out at six different levels show that the clay in this area is somewhat overconsolidated, *Figure 4.2*. This overconsolidation is about 30 kPa at a depth of 3 metres, after which it drops to 15 kPa between 5 and 10 metres. CPT soundings show that the clay is homogenous and that no connected draining layers are present in the top 18 metres.

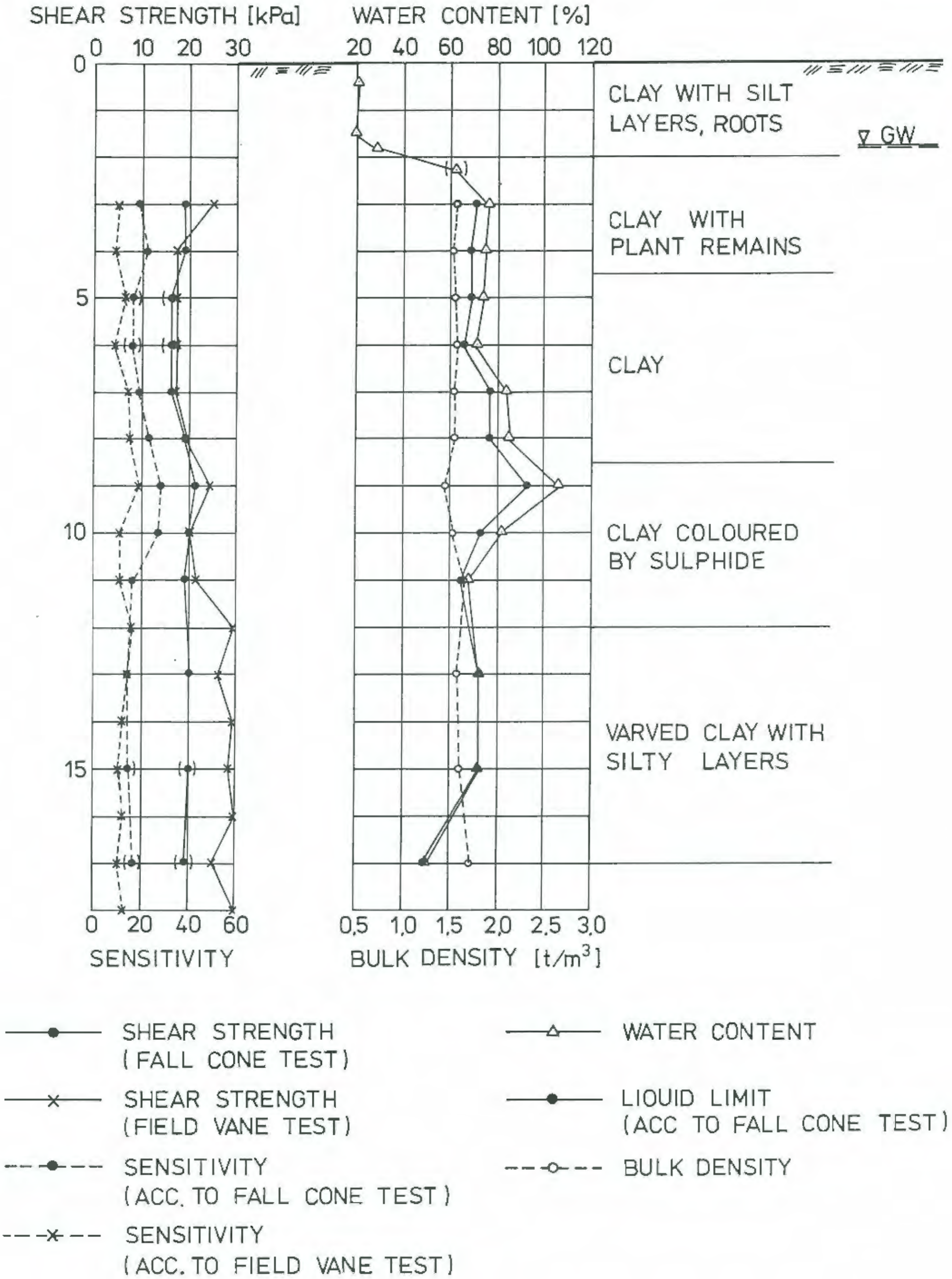


Figure 4.1 Soil profile in the test field at the Linköping marina.

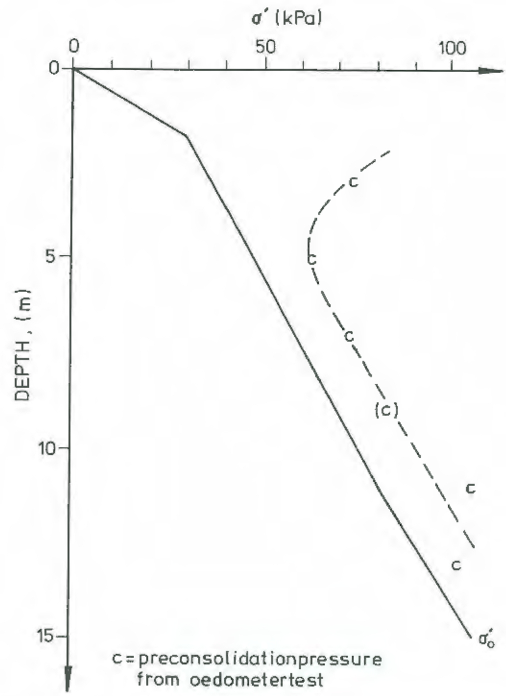


Figure 4.2 Effective vertical stress and preconsolidation pressure versus depth in the test field.

4.2 OUTLINE OF THE TEST FIELD AND OPERATIONAL STRATEGY

General outline

The test field comprises two high temperature heat stores, a store for alternate freezing/thawing, a reference area, a measurement centre and a heat supply centre, *Figure 4.3*. The heat stores were positioned in such a way that they would not thermally influence each other. Each store is cubic in shape with a storage volume of 1000 m^3. In the reference area, natural variations of settlements and pore water pressure were observed.

Design temperatures

The design temperature of a seasonal ground heat store is dependent on the temperature level (heat carrier fluid) of the heat supply (e.g. solar heat) and user demand (house load). Solar heat is frequently produced in a temperature range between 25-75 °C. In extreme conditions, the fluid temperature may temporarily

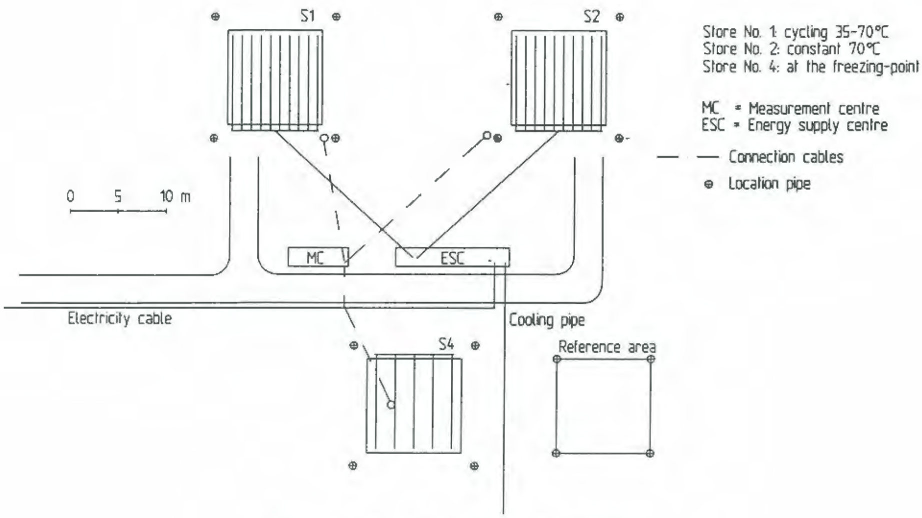


Figure 4.3 Test field in Linköping.

exceed 100 °C. The demand temperature is characterised by requirements on domestic hot water (60 °C) and other factors such as the temperature of floor heating systems (20/30 °C). To meet these temperatures and at the same time ensure satisfactory operation of the pilot plant, the store temperature was set to 35-70 °C.

The heat store installation is not connected to an actual energy consumer. During the limited operating period of three years, the process was accelerated by increasing the number of heating seasons to two cycles per year, each lasting six months, corresponding to a total of six heating seasons. The rate of energy charge/ discharge for each period, corresponding to a development in store temperatures, was decided on the basis of practical reasons. Thus, there is no operational relevance with respect to a fictive user demand for heat or to a specific research strategy within each cycle.

Heat store No. 1 was intended to simulate a seasonal application with varying storage temperature between 35 and 70 °C. Each subsequent heating and cooling period lasted for 3 months, *Figure 4.4*. In heat store No. 2, the storage temperature was kept constant at 70 °C. This procedure made it possible to distinguish effects of temperature variations from effects due to the high temperature alone.

Store No. 4 was designed to simulate combined heat and cold storage. The temperature was intended to be varied around the freezing point with two cycles

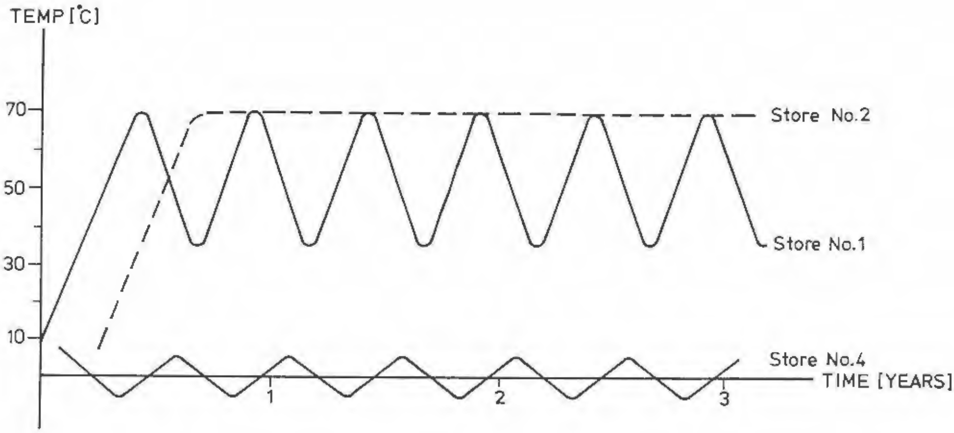


Figure 4.4 Design store temperatures in the heat stores at the test field.

per year. When clay is cooled below the freezing point, advantage is taken of the latent heat released during a phase transformation of present water in the clay from a liquid to a solid state. Only a small volume around each ground heat exchanger was expected to freeze.

4.3 HIGH TEMPERATURE AND FREEZE/THAW STORES

Design of ground heat exchangers

Heat stores in clay are usually made up of a number of connected vertical U-shaped ducts and the natural clay. Each U-shaped duct constitutes one ground heat exchanger. By circulating a heat carrier fluid in the duct system heat is exchanged to and from the storage region.

The ground heat exchangers were dimensioned on the basis of the requested heat transfer capacity. At first, the heat quantity for each store was calculated using the formula

$$Q = V \cdot C \cdot \Delta T \qquad \text{[kWh]} \qquad (4.1)$$

where Q is the heat quantity of the store which corresponds to the amount of charged energy, V is the volume of the store, C is the volumetric heat capacity of the store medium and T is the range of the storage temperature during one cycle. For heat store No. 1 the following values were used

$V = 1{,}000\ m^3$
$C = 1\ kWh/m^3\ °C$
$\Delta T = (70\text{-}30)\ °C$

For example, a change in the storage temperature of 1 °C theoretically changes the storage quantity by 1 MWh for the particular volume.

The heat supply rate, $\dot{Q}$, was calculated by

$$\dot{Q} = Q/t \qquad [kW] \qquad (4.2)$$

where t is the number of hours for each period of energy charge, in this case estimated at 2,000 hours. In addition, the calculated heat supply rate had to be compensated for expected heat losses. For heat store No. 1, the calculated heat supply rate was increased by a factor of 1.45 and consequently it was calculated at 29 kW. The heat supply rate of heat store No. 2 was calculated in a corresponding way at 32 kW, by assuming a multiplication factor of 1.60 because of a higher mean temperature compared with heat store No. 1.

The requested heat transfer capacity for the system of ground heat exchangers was then calculated by dividing the heat supply rate by the operating temperature, i.e. the difference between the fluid temperature and the storage temperature. The temperature difference was assumed by experience to be 10 °C.

The number of ground heat exchangers corresponding to the requested heat transfer capacity was then calculated with the aid of a computer programme, GHE (Hellström 1989:1). The properties of the ground heat exchangers and the soil, store volume, configuration and depth of the ground heat exchangers and the thermal resistance between the heat carrier fluid and the ground were given as input data. For heat stores No. 1 and No. 2, the calculations resulted in a total of 100 ground heat exhangers consisting of single U-pipes distributed in a quadratic pattern with a spacing of 1 metre. The storage capacity of the store with freeze/thaw cycles, store No. 4, was estimated with respect to latent heat released during phase transformation of water present in the soil. For store No. 4, the calculations resulted in a total of 24 ground heat exchangers made up of single U-pipes in a quadratic pattern with a spacing of 2 metres. The design of the stores is described in detail by Bergenståhl et al (1990).

The duct must be able to withstand high temperatures without any change in its strength characteristics. It has to be flexible to facilitate installation. Turbulent flow in the ducts must be guaranteed during operation and the pressure drop should not be too high. Small duct dimensions reduce the material costs. For these reasons, a duct made of reinforced polyethylene (PEX) with an outer diameter of 25 mm and a wall thickness of 2.3 mm was chosen (pressure class 0.6 MPa at 90 °C).

The ground heat exchangers in the high temperature stores were divided into ten parallel connected duct loops, each loop comprising ten ground heat exchangers, *Figure 4.5* and *5.1*. The freeze/thaw store consisted of two parallel connected duct loops, each loop comprising 12 ground heat exchangers, Figure 5.7. To reduce the risk of buckling of the ducts because of expected settlements in the stores, the ducts were installed with an inclination of about 10:1 (vertical to horizontal).

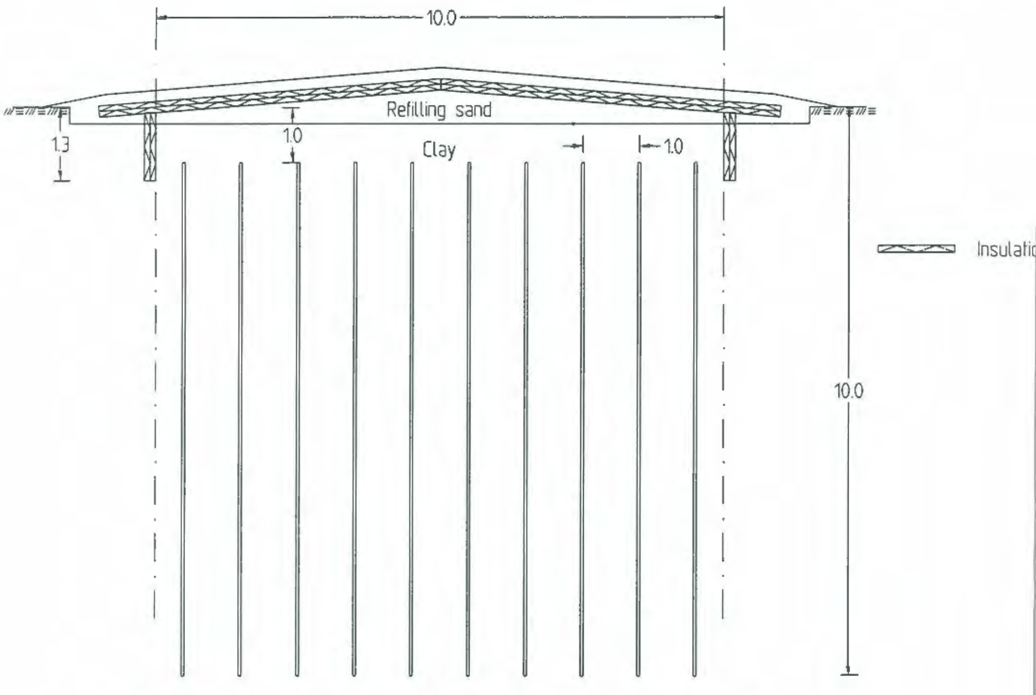


Figure 4.5 Heat store design in principle, vertical section.

Design of store insulation

To reduce heat losses, the high temperature stores were insulated at the top and along parts of the sides. Vertical insulation was found to be economic because of the relatively short operating time. The thickness of the insulation was optimized with respect to investment costs for the insulation and energy costs. Two different insulation qualities were chosen as previously described in Chapter 2.3.

The high temperature stores were insulated with two layers of polystyrene foam, 2 x 0.1 m, at the top and vertically along three sides down to about 1 metre depth. The insulation was provided with a foil on the surface in contact with the soil to protect the insulation from moisture and limit the vapour diffusion from the stores. At the top, half of each store was designed with extruded polystyrene (XPS) supplemented with a foil underneath made of plastic and aluminium laminate and the other half with expanded polystyrene (EPS) supplemented with a plastic PVC foil. The values of the thermal conductivity given by the manufacturers were 0.030 and 0.036 W/m°C for extruded and expanded insulation respectively, *Table 4.1*.

Table 4.1 Thermal conductivity in W/m°C of extruded (XPS) and expanded (EPS) insulation.

	Thermal conductivity [W/m°C]	
Type of conductivity	XPS	EPS
λ_{kl} (classified)	0.030	0.036
λ_p (in practice)	0.034	0.049 [1]
		0.036 [2]

1) Ground against both sides.

2) Ground against one side.

The practical value of the thermal conductivity of the insulation is determined by the manufacturers with a special method which to some extent simulates the effects of practical use. The method includes tests such as submersion of the insulation in water.

Vertical insulation consisting of extruded polystyrene supplemented with a plastic PVC foil was chosen for practical and economic reasons. The depth of the vertical insulation corresponded to the length of one insulation panel (1.2 metres). The ducts to and from the store were concentrated to one side of the two heat stores and for practical reasons it was decided not to insulate this side of each store.

In order to create a smooth foundation and minimise the risk of puncturing the protective foil, an inclined layer of compacted sand formed the base for the insulation. The inclination was based on expected settlements while retaining the ability to disperse precipitation. The cover formed a central ridge with gentle slopes towards the sides, *Figure 4.8*.

The positions of installed measuring equipment, the sites for future field investigations and the position of wires from installed electrical sensors were carefully documented. To facilitate field tests and samplings, short casings of PVC through the top insulation were used. A cover of filling sand about 0.2 metre thick was laid over each high temperature store.

Construction, duct installation

The construction of the heat stores was largely performed by personnel from the SGI.

In order to increase the cost-effectiveness of heat stores in clay, an improved method for duct installation was designed (Lehtmets 1993). Previously, each ground heat exchanger was installed separately and joined manually with a mechanical coupling. With the improved method, connection work is essentially omitted at duct installation, see *Figure 4.6*. The method permits duct sections of up to 250 metres (10 ground heat exchangers) to be installed continuously without couplings. Couplings are used only for joining the ducts to the main supply pipes. Furthermore, by using a continuous duct feed it is possible to interrupt the installation, for instance when an unexpected obstacle is encountered in the clay, without any disturbance to the on-going installation of the duct section. When very loose clay is encountered it may be necessary manually to pull out a length of duct corresponding to the store depth before applying the installation tool. If the clay is very loose, the feed from the duct reel may not work properly, i.e. at installation the contact resistance between the clay and the previously installed duct does not exceed the friction resistance in the hose reel.

The installation tool consists of a wheel with a diameter of 0.35 m connected to a fork. The wheel has a recessed channel to hold and protect the plastic pipe during installation. The tool is connected to a series of jointed extension rods at installation.

Before duct installation started at the test field, the topsoil of the store areas was removed. Trenches about 0.3 metre wide and 1 metre deep were excavated across the store. For installation of the ducts, a cross-country vehicle equipped with a geotechnical drill rig was used which straddled the trench, *Figure 4.7*. The trench protects the duct from damage in the stiff dry crust clay, at the same time as the

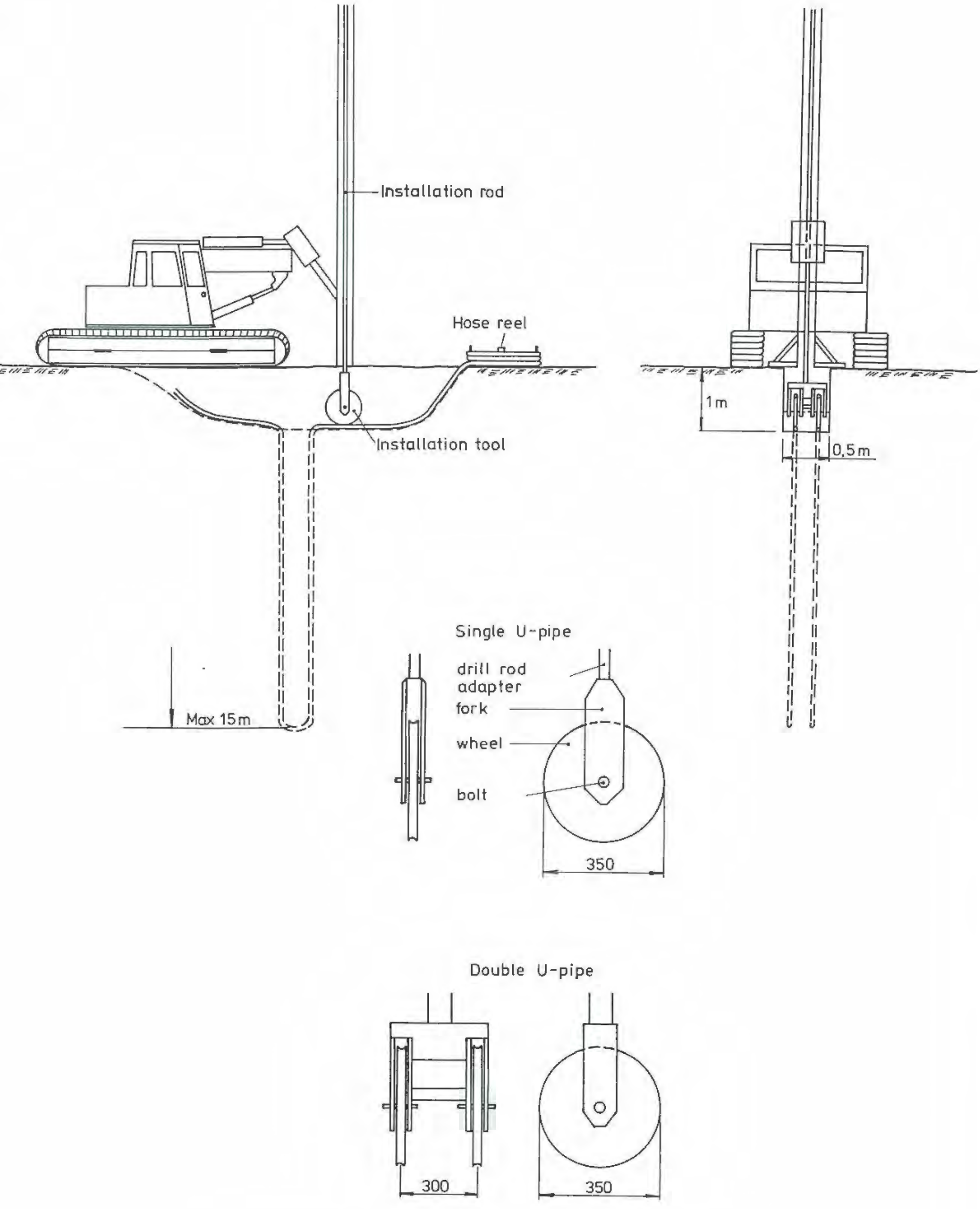


Figure 4.6 Duct installation method and tool.

Figure 4.7 Duct installation in a trench using a drill rig.

softness of the underlying clay permits a smooth transition to the following ground heat exchanger.

The duct was laid out on the bottom of the excavated trench. The installation tool was then applied to the duct and pushed into the clay. To better withstand effects of expected settlements, the ducts were installed with a limited inclination, about 10:1. At the desired installation depth of 10 metres below the surface, the tool was hoisted above the surface, leaving the duct in the ground. The machine was then moved along the trench to the next installation point and a new ground heat exchanger was installed using continuous duct feed from a reel placed in front of the jeep. Parallel trenches for duct installation were alternately excavated and refilled after installation by means of an excavator. A total of 5,000 metres of ducts were installed in the two heat stores during six working days. About 500 metres of ducts were installed in the store for alternate freezing/thawing.

In a parallel study, installations were performed using a lime column machine. An installation tool for a double U-pipe was then used. The capacity of the lime column machine was greater, enabling the installed length of duct per time unit to be quadrupled compared to the geotechnical drill rig. The greater capacity was primarily possible due to the replacement of labour intensive connection/ disconnection of rods with a single stroke at installation by the lime column machine. Double U-pipes were installed to a depth of 15 metres and 500 metres of duct were easily installed in less than one hour.

After installation, all duct loops were tested for tightness. From comparisons of obtained diagrams of pressure drop versus time for the different duct loops, one loop in heat store No. 2 was found to be leaking. The damage probably occurred at installation by collision with a settlement gauge. The broken loop was disconnected.

Placing of insulation and sand fill cover

The vertical insulation was placed in excavated trenches along three sides of the high temperature stores. A layer of sand was placed on top of the heat stores with the aid of an excavator and then compacted to form a smooth base for the top insulation. The insulation panels were laid out manually with a small inclination from the store centre to opposite store borders. The panels placed directly against the sand fill were delivered to the site with a protective foil on one side. The panels were connected with easily fitted plastic joiners.

The insulation work was time-consuming because of extensive hole making for the previously installed pipes for the measuring equipment. Expandable insulation foam was used to fill out the spaces between the pipes and the insulation and also between the insulation panels at the top of the heat stores, *Figure 4.8*. The pre-glued foil sometimes became detached from the insulation panels. For a heat store with no instrumentation it is probably better to lay out the foil, which is delivered in a roll, separately from the panels.

Casings of PVC pipes 0.1 metre in diameter were installed through the insulation and the sand fill underneath in order to facilitate future field investigations. The interior of the pipes was filled with sand and cut-out pieces of insulation. The high temperature stores were eventually covered with approximately 0.2 metre of sand fill which was compacted with a hand operated compacting machine. The store for alternate freezing/thawing was covered with previously excavated soil within the test field area immediately after duct installation was completed.

Figure 4.8 Heat store No. 1 showing the top insulation before covering it with a sand fill.

Installation of measuring equipment

The major part of the measuring equipment in the high temperature heat stores was installed just before laying the top insulation. An ordinary geotechnical drill rig was used except for the installation of the temperature sensors. The temperature sensors were mounted on a PVC pipe and pushed into pre-drilled holes by hand. Additional temperature sensors were later installed with an alternative method where the temperature sensors were left hanging freely inside pre-installed pipes later filled with a suspension of bentonite. The instrumentation of the heat stores is described in detail in Chapter 5.

Wires from the automatic sensors were drawn in underground pipes to the measurement centre installed in a mobile workmen's cabin where they were connected to logging units. The data collection programme was then arranged for automatic registration and calibration of the signals from the sensors.

4.4 HEAT SUPPLY CENTRE

Design

The design of the heat supply centre was based on demands regarding function and performance, system layout, choice of major components and economic concerns.

For economic reasons, the heat supply was designed to be covered by electricity.

The electricity was converted to thermal heat by an electric boiler with a secondary side using water as heat carrier fluid. For extraction of heat from the stores, water from a nearby river was used at moderate demands on low temperatures and a cooling machine for temperature requirements below 0 °C. The heat was distributed to the heat stores in parallel systems separated by heat exchangers. Heat exchangers prevent not only the mixing of water, which was the general heat carrier fluid, and the calcium chloride mixture used in the parts of the distribution systems operated below 0 °C, but also the negative influence of oxygen diffusion through the plastic ducts, which may support corrosion processes. The secondary side of each heat exchanger comprised circulation pumps, manifolds and valves for the indoor connection of each parallel loop of the ground heat exchanger. A schematic outline of the heat supply centre is presented in *Figure 4.9*. The total heating capacity was 50 kW and the total cooling capacity 30 kW.

For maintenance reasons, each duct loop could be disconnected and closed or adjusted by valves. Except for traditional instrumentation and regulation equipment the heat supply was designed with regard to research aspects. The heat supply was either regulated with a constant output temperature or a constant heat output (no flow rate regulation). The change in operating mode was made manually. The delivered amount of energy, together with temperatures and fluid flow was measured and manually recorded.

Construction

Procurement and construction of the heat supply centre were performed by external contractors to specifications from the SGI. The energy supply unit was built into a 40 ft. shipping container. The construction work included plumbing, electricity supply, control and regulation equipment and pipe insulation.

The ready-made energy supply centre was transported to the site and lifted into place, after which the ducts to and from the stores were connected. The energy supply plant was pressure tested and adjusted before starting up. Electricity was provided to the test field by the municipal energy company.

Cooling pipes, 300 metres in length, were laid out between the energy supply centre and the river at a depth below the frost limit. The inlet and outlet of the cooling pipe were supplied with filters and placed wide apart in the river at sufficient depths to avoid damage. Inspection wells were placed at the lowest and highest points along the pipe to enable access for supervision, (deaeration and emptying of the system).

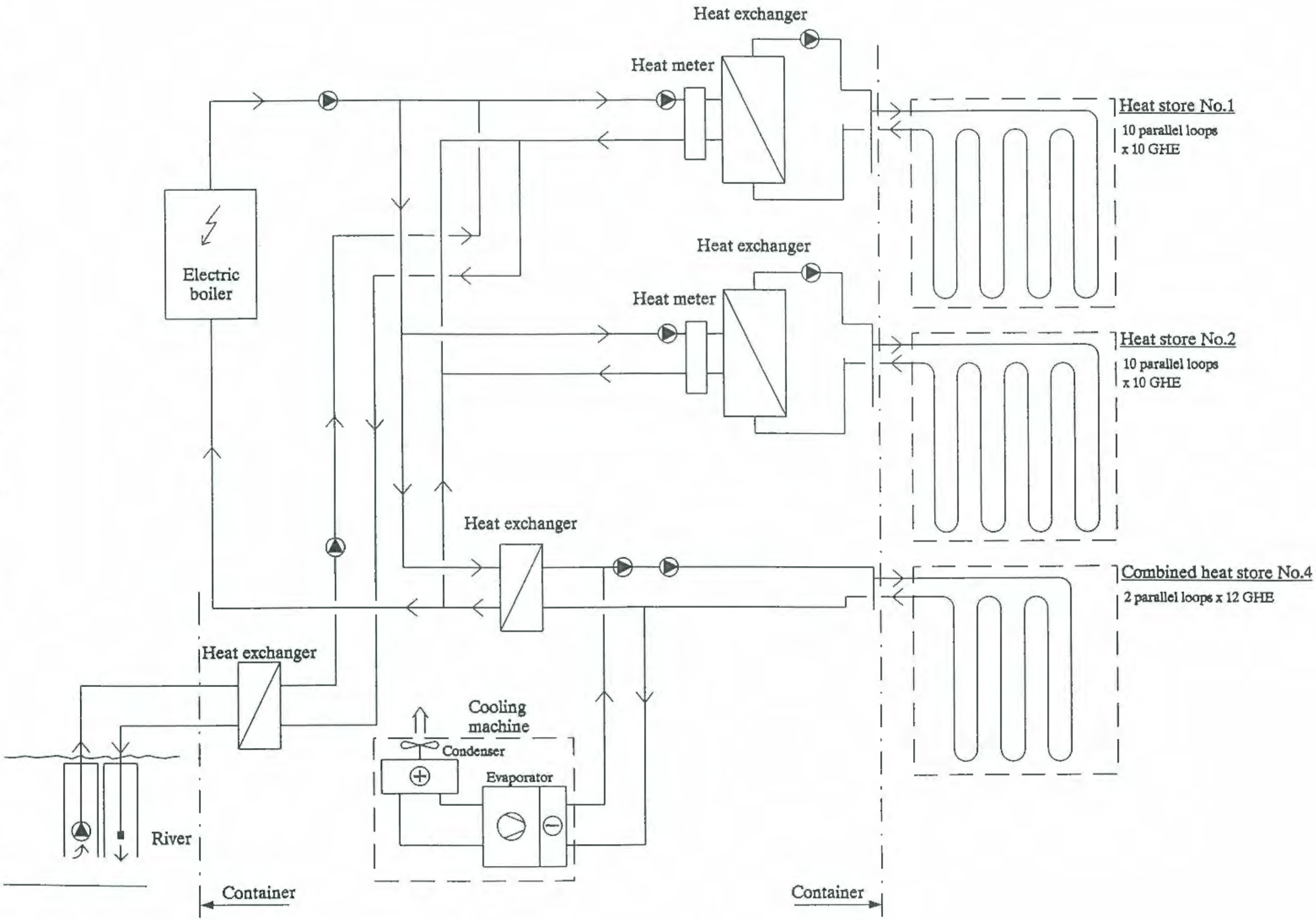


Figure 4.9 Schematic layout of the heat supply centre.

Chapter 5.
Instrumentation and measuring methods

Monitoring was performed with conventional geotechnical methods and equipment, in spite of the high ground temperatures which probably reduced the measuring accuracy. To eliminate unexpected effects of the high temperature, more than one system was often used for measuring temperature, pore water pressure and settlements.

Measuring instruments were installed at the centre of the stores, at the borders of the stores and at specific distances outside the stores. Instruments in the stores were installed at three levels: 3.5, 6 and 9 metres depth, and at one level below the store base: 12 metres depth. The investigations were mainly carried out within a 4x4 metre area in the centre of each store, where the influence of boundary effects was assumed to be small.

The recording system consisted of a personal computer, two logging units with 24 channels each and a programme for data management. The equipment was placed inside a mobile measurement centre at the site. Temperatures and settlements in the heat stores were measured automatically. Automatic recording of the pore water pressure was performed during the first year of operation. The temperature was also read manually via a connection panel. Measured values from automatic sensors were collected every three hours. Data collection was performed continuously, with minor interruptions, since the operation of the test field started in February 1992. In this report, one value per day has been used in plotted diagrams.

Natural seasonal variations were observed within a reference area. Pore water pressures were measured in open standpipes at five different levels: 3.5, 6, 9, 12 and 19 metres depth. The distribution of the vertical movements was measured with a bellows hose settlement gauge.

5.1 EFFECTS OF HEATING ON THE GEOTECHNICAL BEHAVIOUR OF CLAY

Settlements and horizontal movements

The position of installed equipment for measuring vertical and horizontal deformations in heat store No. 1 is shown in *Figure 5.1*. The instrumentation of heat store No. 2 was similar to heat store No. 1.

Total settlements of the top surface were measured with automatic settlement gauges installed in the centre of each high temperature store. The automatic settlement gauge measures the position of the ground surface in relation to a point at a greater depth. In principle, the settlement gauge can be divided into an inner and an outer system where the inner system is fixed in firm ground at a greater depth and the outer system rests on the ground surface. The vertical displacement of the outer system in relation to the inner system is measured with a potentiometer at the ground surface, *Figure 5.2*.

The thermal expansion of the inner pipe must be taken into account when evaluating the result. The accuracy of the automatic settlement gauge is normally estimated at 0.1 mm.

Settlements of the surface were also determined from measurements of a horizontal hose settlement gauge, normally used for measuring settlements under embankments and footings (Bergdahl 1984). A plastic tube was installed horizontally at 1 metre depth along the centre line of each store, reaching approximately 10 metres outside the store on both sides. The tube followed the vertical displacement of the ground.

The measuring equipment consists of a plastic hose with an inner hose connected to an encapsulated pressure transducer, a tripod and a read-out unit, *Figure 5.3*. The space between the outer and inner hose is filled with water in connection with the atmospheric pressure at the upper end and to the pressure transducer at the lower end. The inner pipe encapsulates the electric cable from the transducer.

Measurements are performed by inserting the measuring head into the pre-installed tube in the ground. The measured hydrostatic pressure in the transducer corresponds to the vertical distance between the water level at the surface and the position of the transducer. The reference water level is constant and measured by levelling. In this way, the vertical position of the horizontal tube may be obtained.

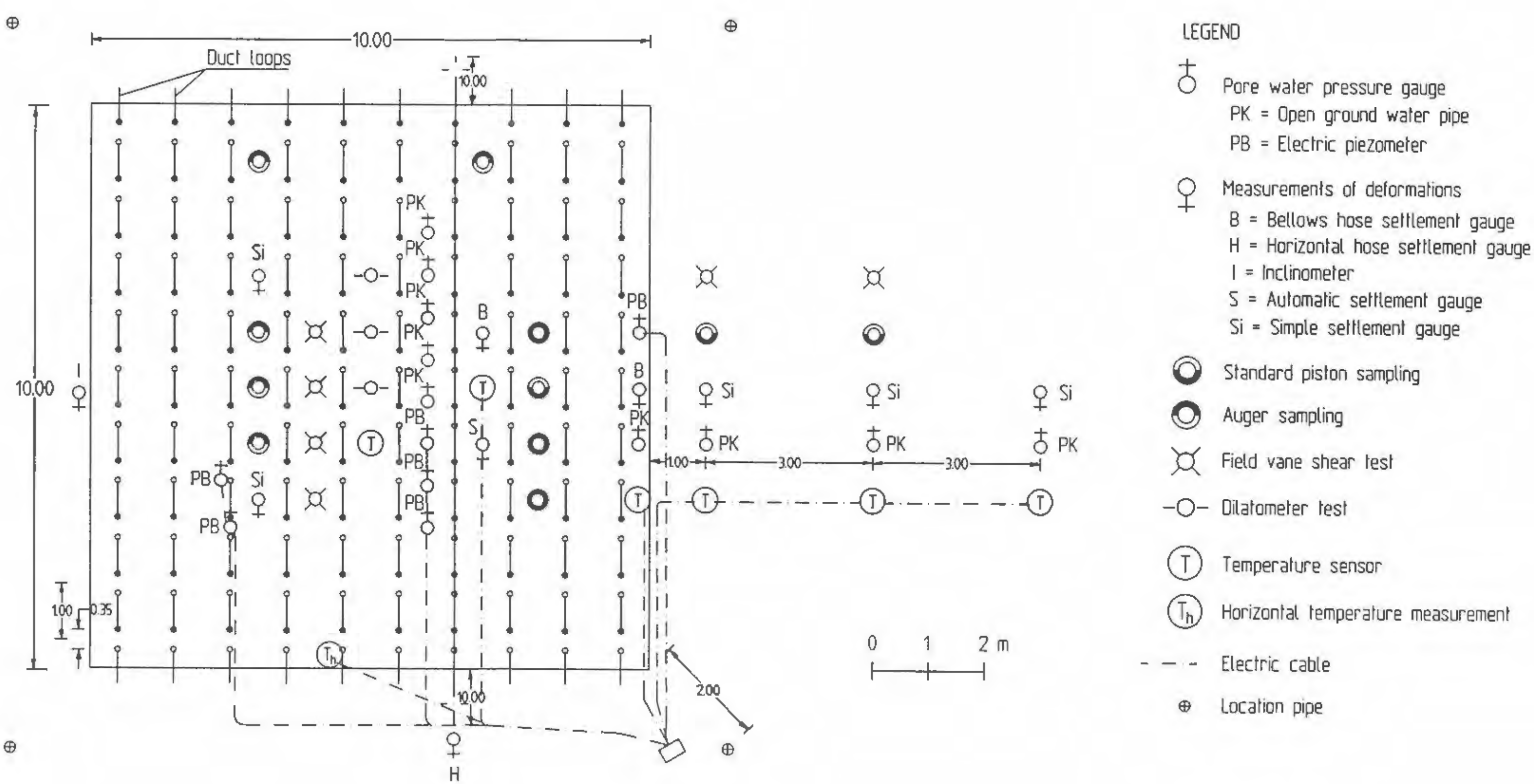


Figure 5.1 Location of instruments in heat store No. 1.

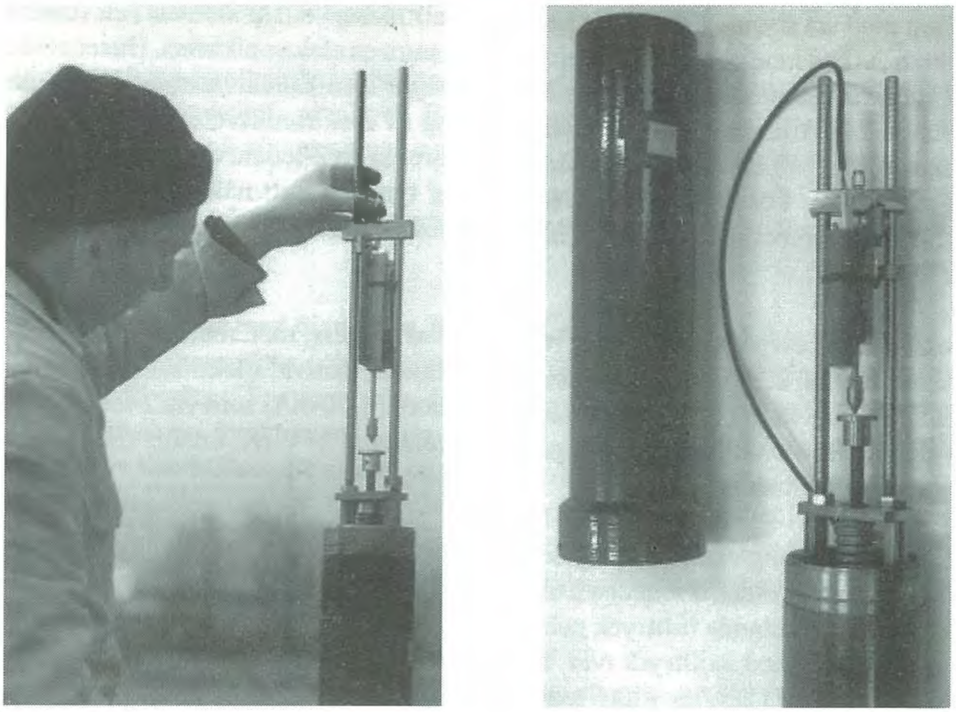


Figure 5.2 SGI automatic settlement gauge (Möller & Åhnberg 1992).

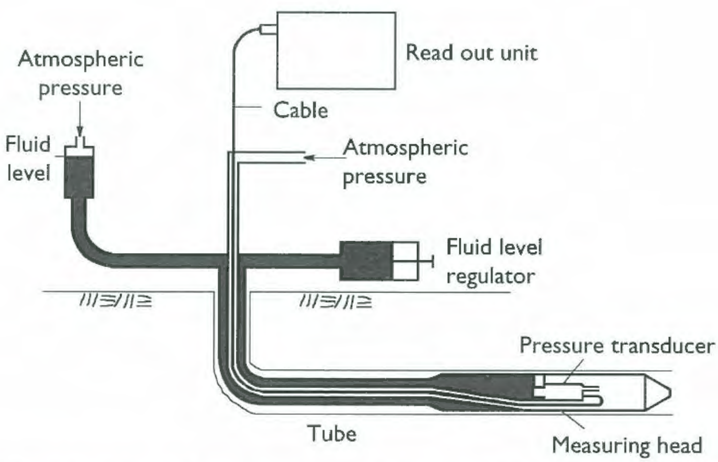
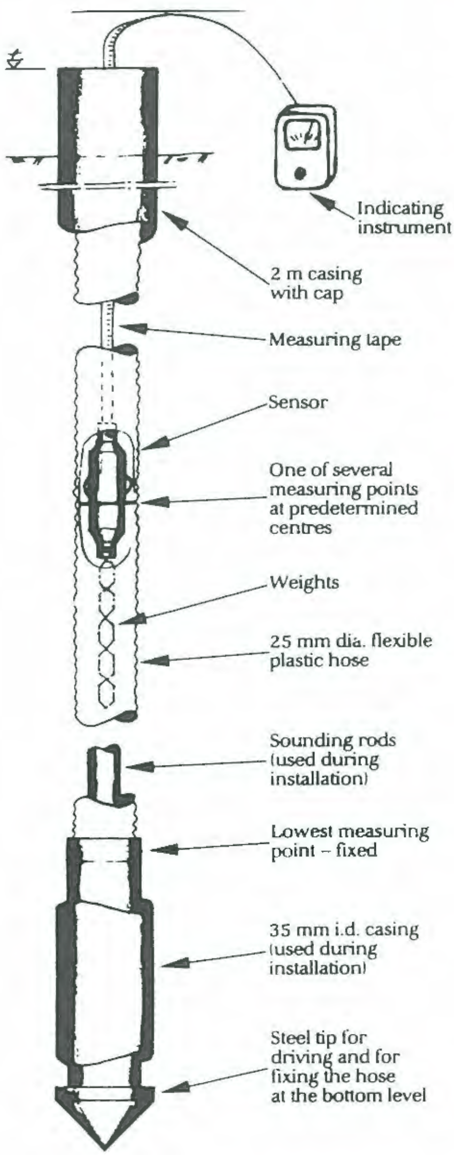


Figure 5.3 Principle of the measuring unit for the SGI horizontal hose settlement gauge.

The system is somewhat sensitive to temperature effects. In order to equalise temperature differences, measurements were made with a continuous water flow through the tube. This procedure improves the accuracy of the measurements in the current circumstances, which is estimated at ±5-7 mm based on field experience. The accuracy under normal conditions is ±1-2 mm.

The vertical distribution of the settlements was measured with bellows hose settlement gauges, *Figure 5.4*. The bellows hose consists of a plastic hose which is flexible in the vertical direction. The method is based on the condition that the bellows hose interacts closely with the surrounding soil. The maximum relative compression of the bellows hose is limited to 10 %.

Settlements of the surface were also determined by levelling of the ground surface at specific distances from the store boundaries. Settlements at 3 and 6 metres depth inside the stores were measured with simple settlement gauges. The simple settlement gauge consisted of an enlarged screw-shaped plate (∅ 100 mm) installed at the design measurement level and connected to the ground surface with steel pipes.



The bellows hose is provided with metal rings at 1 metre equidistance. Measurements are performed by lowering a sensor connected to a measuring tape of steel into the hose. Whenever the sensor reaches a metal ring, an electrical circuit is closed, resulting in a deflection on an instrument at the ground surface so that the position of each metal ring can be read on the measuring tape. The normal measurement accuracy is estimated at ±1 mm.

Figure 5.4 Components of the bellows hose settlement gauge (Bergdahl 1984).

Horizontal movements

Horizontal ground movements were measured with inclinometers at the boundaries of the high temperature heat stores in two directions, parallel and perpendicular to the boundary, *Figure 5.5.*

Measurements are performed in a vertical plastic pipe, with the lower end inserted in a firm bottom layer where no horizontal deformations are supposed to occur. The stiffness of the pipe is adapted to follow the movements of the soil. The inclinometer measures the inclination in two different directions in the pipe, normally at 1 metre equidistance. The contour and position of the inclinometer tube is determined by integration of the inclinations and the distances between the measuring levels. The horizontal movement is then obtained in relation to the position at the zero reading after installation of the inclinometer tube and before any heating/cooling of the ground has taken place.

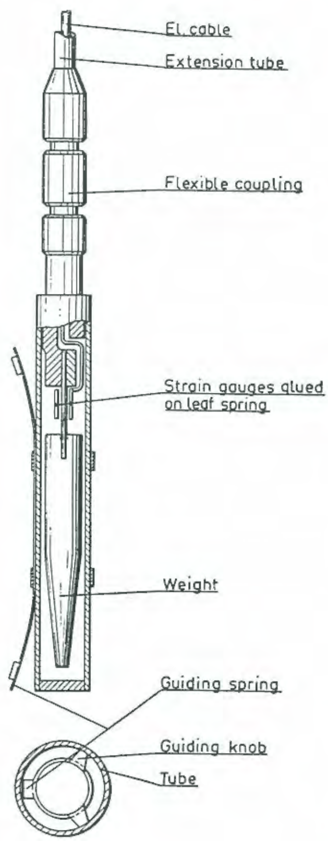


Figure 5.5 SGI inclinometer (Kallstenius 1961).

The temperature in the inclinometer pipe varied significantly with the depth, which made it necessary to calibrate the measuring device for different temperature levels. Each measured value along the pipe was transformed individually to a corresponding inclination. Because of this procedure it is assumed that the accuracy was less than under normal geotechnical conditions. The accuracy of the SGI inclinometer is normally estimated at ±6 mm/20 m.

Pore water pressure

The pore water pressure was measured manually in a system of open ground water pipes and initially with electric strain gauge piezometers. The position of installed equipment for pore water pressure measurements is shown in Figure 5.1.

The ground water pipes (KADO) consist of PVC pipes with an inner diameter of 13 mm and a filter of geotextile 0.15 metre in length. A layer of silicone oil was supplied on the water surface to reduce the effects of evaporation. In the winter, a small amount of glycol solution was poured into the standpipes to reduce the risk of freezing at high water levels in the standpipes. Measurements of the water level in the pipes were performed by lowering a signal cable. When the cable reached the water surface in the pipe the electrical circuit was closed, resulting in an indication on an instrument.

The pore water pressure was also measured automatically during the first year of operation by electric strain gauge piezometers (BAT) at two depths, 6 and 9 metres, in both heat stores and at 3.5 metres depth in heat store No. 1. Additional piezometers were also installed close to a ground heat exchanger in heat store No. 1.

The BAT piezometer is a closed system comprising a special filter tip, a pressure transducer and a read-out unit, *Figure 5.6*. The filter tip consists of a porous filter and a chamber closed at the top by a rubber membrane. Measurements are performed by lowering an electrical pressure transducer onto the tip, by which a hypodermic needle attached to the transducer penetrates the rubber membrane and enters the water-filled chamber. Water contact is established through the needle to the transducer. In this way, the pore water pressure is measured at the filter depth by the transducer and registered at the ground surface.

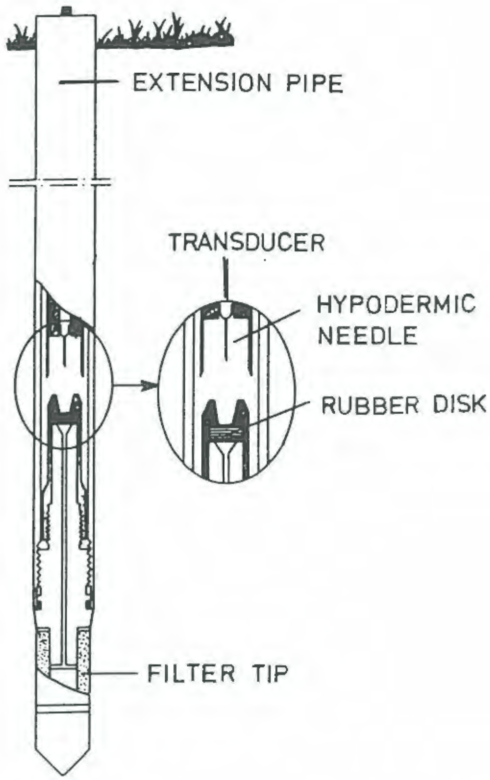


Figure 5.6 BAT piezometer (Tremblay 1989).

At the test field a filter made of HD polyethylene, 30 mm in diameter and 40 mm in length, and a tip of stainless steel was chosen. A pipe of stainless steel was also used next to the filter tip in order to prevent corrosion which may develop if different materials are used. An electrochemical process may result in the production of gas in impermeable soils and thereby disturb the measurements.

A direct comparison between the readings from automatic pore water pressure gauges and open standpipes cannot be made when the pore water pressure changes rapidly, because the standpipes react more slowly.

Temperature

The temperature in the heat stores was measured with Pt100 sensors, a type of resistance thermometer. Resistance thermometers utilise the known temperature dependence of the resistivity of a metal, in this case platinum. The temperatures were measured at the same depths and positions as the pore water pressures.

The Pt100 element was encapsulated by a steel cover and supplied with a PVC insulated 4-wire cable. The sensor was sealed with silicone to protect it from moisture. The sensors were classified according to DIN 43760 with an accuracy of ±0.3 °C at 0 °C and ±0.8 °C at 100 °C, being linear in between.

The calibrated temperature sensors were connected to logging units and to an instrumentation panel for manual readings.

Samplings and laboratory investigations

Changes in the geotechnical properties of clay were studied by investigating undisturbed clay samples obtained by standard piston sampling.

Undisturbed samples of the clay were taken at three depths within the heat stores, 3.5, 6 and 9 metres and at one depth under the stores, 12 metres. The pore water pressures and temperatures were measured at the same depths. Piston samples were taken three times during the first energy charge of heat store No. 2 and subsequently every six months at a store temperature of about 70 °C in both heat stores. No specific measures were taken to prevent cooling of the samples during transportation to the laboratory. The temperature of the samples at the laboratory examination varied between 20-40 °C.

Examinations in the laboratory were made with respect to density, water content, liquid limit, sensitivity and shear strength. The liquid limit defines the water content where the clay in a remoulded state changes from a liquid to a plastic consistency. The sensitivity gives the relationship between the undrained shear strength before and after remoulding. Sensitivity is an important factor when estimating the shear strength reduction in excessive undrained shear deformations.

In situ tests

In situ measurements of the shear strength of the clay were performed in the heat stores down to a depth of 15 metres by field vane shear tests and dilatometer tests. The field vane shear test is performed by pushing a vane into the soil and rotating it, while measuring the resistance to rotation. The shear strength is calculated from the dimensions of the vane and the maximum torsional moment thus obtained. The investigations were performed according to the standard for field vane shear tests recommended by the Swedish Geotechnical Society (1993).

The dilatometer test is performed by pushing a rectangular steel plate to the desired testing depth. In the centre of one side of the plate is a circular steel membrane which is expanded at the test levels by applying a gas pressure. The expansion pressure with respect to horizontal displacement of the membrane is used together with the initial pore pressure and effective vertical stress to evaluate the undrained shear strength of the clay. The dilatometer tests were performed according to the standard recommended by the Swedish Geotechnical Society (1995).

In situ tests were performed during the initial heating of heat store No. 2, and 1-2 times per year at a store temperature of 70 °C in both heat stores corresponding to the time of sampling.

5.2 EFFECTS OF FREEZING ON THE GEOTECHNICAL BEHAVIOUR OF CLAY

The instrumentation and investigations in the store with varying temperature around the freezing point, Store No. 4, were similar to those in the high temperature heat stores (Chapter 5.1), but less extensive, *Figure 5.7*. Special equipment was installed to enable monitoring of the horizontal extension of the frozen zone around a ground heat exchanger and the settlements of the expected frozen soil around the ground heat exchangers.

A device for measuring the location of the freeze-front was developed on the same principles as conventional frost depth indicators. The equipment consisted of a plastic pipe with an inner plastic hose filled with a temperature sensitive liquid. The tube was installed with one end above the ground surface and the lower end positioned between the vertical shanks of a ground heat exchanger, at about 2 metres depth. The liquid changes from blue to colourless when it freezes, whereby the horizontal movement of the freeze-front was intended to be observed.

Equipment for measuring both settlements of the thawing soil and the soil unaffected by freezing was installed. To enable observation of the settlements of previously unfrozen soil below the uppermost layer, concrete well rings (∅ 0.6 m) were installed above three of the ground heat exchangers, through the upper crust. Inside the well rings, simple settlement gauges were installed for measurements of the vertical displacement at 2 and 5 metres depth by levelling, *Figure 5.8*. The gauges consisted of an enlarged screw-shaped plate at a specific depth connected to the bottom of the well by extension rods. Settlements of the unaffected soil were measured with a horizontal hose settlement gauge and a bellows hose settlement gauge. During the monitoring period, additional levellings of the ground surface were also performed in the store.

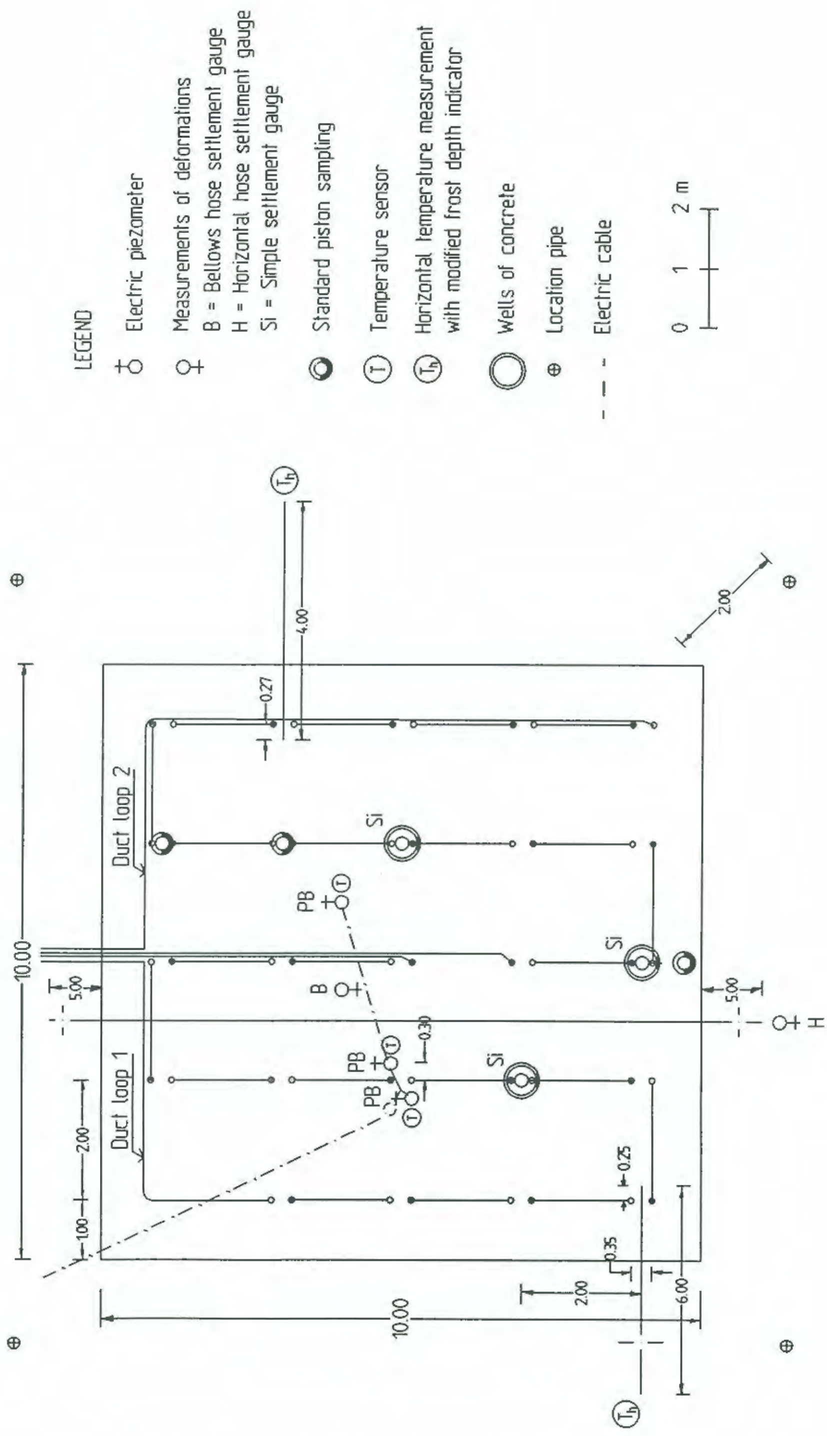


Figure 5.7 Instrumentation of heat store No. 4.

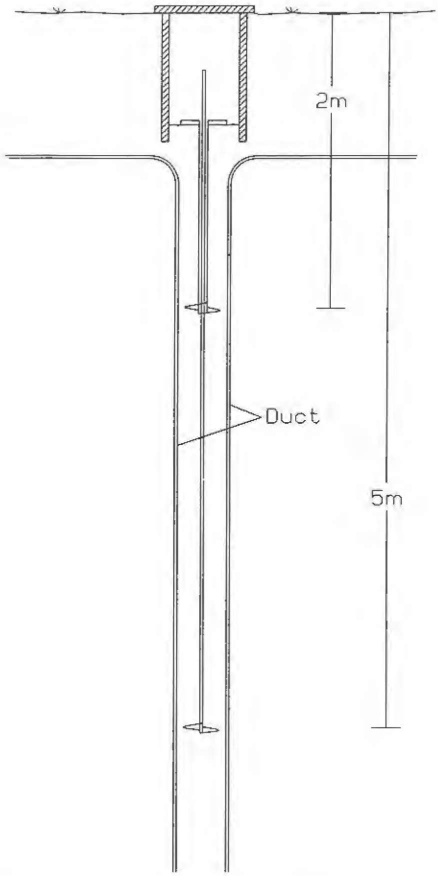


Figure 5.8 Settlement gauges in well rings in heat store No. 4.

In Store No. 4, three electric strain gauge piezometers (BAT) were installed, two of them for automatic registration and the third for manual readings. The piezometers were installed in the middle of the store at 6 metres depth and at corresponding distances from a ground heat exchanger where the temperature was measured; immediately outside the expected frozen zone (about 0.3 metre) and 1 metre away. One piezometer was installed at 11.5 metres depth.

The temperature in the store was measured with two Pt 100 sensors at 6 metres depth, about 0.3 and 1 metre from a ground heat exchanger in the middle of the store, respectively. The temperature was also measured at 11.5 metres depth (1.5 metres below the lower end of the ducts).

The geotechnical properties of the soil were investigated by examining samples obtained by standard piston sampling. Samples were taken after the first cycle of freezing and thawing, in the soil that remained unfrozen, and after the second cycle in the thawed soil that had been frozen.

5.3 THERMAL PROPERTIES OF CLAY AT HIGH TEMPERATURES

Two different methods; calculations with a computer programme and direct measurements, were used to evaluate the **thermal conductivity** of the clay.

The computer programme Condsoil (Sundberg 1991) uses the volume share of mineral particles, pore water and pore gas, together with reference values of the thermal conductivity as input data when calculating the thermal conductivity of the soil. The programme includes a temperature function that takes into account the increased heat transport in unsaturated soil through vapour diffusion at higher temperatures. When supplying the programme with input data, standard values of the thermal conductivity of water and air with respect to the temperature were used.

Clay samples from the heat store influenced by a constant storage temperature of about 70 °C were used. The porosity and the degree of saturation of the different samples were calculated from determinations of density and water content in the laboratory and later used in the calculation of the volume share of soil constituents.

The volumetric **heat capacity** was calculated as

$$C = C_g \cdot (1 - n) + C_w \cdot n \cdot S_r \qquad [\mathrm{kWh/m^3\,°C}] \qquad (5.1)$$

where C_g and C_w are the volumetric heat capacity for soil particles and pore water respectively, n is the porosity and S_r is the degree of saturation.

Thermal properties of soil samples have been evaluated three times during the first heating of heat store No. 2 and subsequently every six months at a store temperature of about 70 °C.

In addition to computer calculations, a number of direct measurements of thermal conductivity were performed in the field. The equipment consists of thermal probes for laboratory and field use, a power unit, a logger and a portable computer (Gabrielsson and Lehtmets 1992). The thermal conductivity of the clay was measured directly in the ground with the thermal probe, *Figure 5.9*.

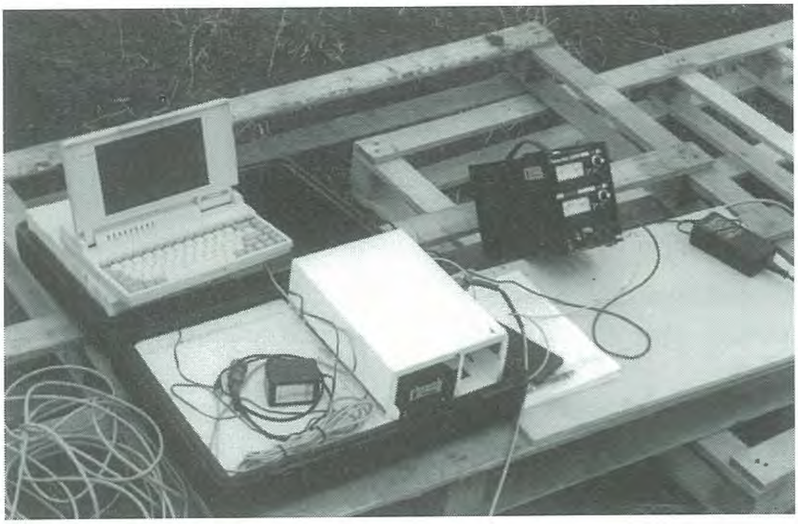


Figure 5.9 Equipment for measuring thermal conductivity with a thermal probe.

The thermal probe encloses a temperature sensor and a heating wire. The thermal probe was carefully installed using a geotechnical drill rig mounted on a jeep. After installation, the probe was supplied with heat at a constant injection rate and the temperature increase with time was measured. The temperature increase is inversely proportional to the thermal conductivity, which is calculated using equation (5.2) developed from the "line source" theory.

$$\lambda = \frac{\dot{q} \cdot ln(t_2/t_1)}{4\pi \cdot (T_2 - T_1)} \qquad [W/m°C] \qquad (5.2)$$

where $\dot{q}$ is the heat output per length metre of probe [W/m], and T_1 and T_2 are the temperatures [°C] at times t_1 and t_2 [s], respectively. It may be observed from equation (5.2) that the temperature increase plotted versus time in a lin-log diagram becomes a straight line. Two points on this line are used to calculate the thermal conductivity.

Thermal probe analysis using the "line source" theory is valid under specific assumptions described for example by Sundberg (1988):

- The probe can be described as a continuous linear line source of infinite length and infinitesimal thickness.

- The heat flow is constant, one-dimensional and takes place radially from the heat source.

- The temperature distribution is homogenous before beginning the test.

- The test material is homogenous and isotropic.

Measurements with the thermal probe were performed once a year in the heat store with a constant temperature of about 70 °C. Initial measurements at normal ground temperature were performed close to the store.

5.4 THERMAL PERFORMANCE OF THE INSULATION

Studies of the thermal performance of the insulation included investigations of the thermal conductivity of the insulation and the water content of the insulation and the sand fill just above and beneath the insulation.

The **thermal conductivity** of the insulation was calculated by measuring the heat flux density through the top insulation with the aid of calibrated heat flux sensors and the temperature along a vertical section through the insulation. The temperature was measured at the top and bottom surfaces of the insulation layer and between two insulation panels in each half of heat store No. 2 with different insulation. One heat flux sensor was placed against the lower surface of the insulation panel closest to the ground in each insulation half. The heat flux sensor had an overall diameter of 110 mm and a thickness of 5 mm.

The heat flux sensor is based on the principle that heat passing through the sensor will generate a difference in temperature between the lower and upper surface of the sensor. The difference is detected with a thermopile formed by a large number of thermocouples in series. The thermopile generates a signal in the millivolt range which may be detected by a multimeter. The corresponding heat flow is obtained by multiplying the measured value with a given calibration factor. The measurements were performed every month with a multimeter connected to the sensors wires at the ground surface.

The thermal conductivity was evaluated in accordance with the theory of heat flow through a plane boundary (Chapter 3.4). For a plane boundary the heat transfer is maintained in the direction from the inner to the outer surface temperature where $T_i > T_o$. The thermal conductivity of the insulation, λ, was calculated by

$$\lambda = \frac{\dot{Q} \cdot b}{A \cdot \Delta T} \qquad [\ W/m°C\ ] \qquad (5.3)$$

where $\dot{Q}/A$ is the heat flux density [W/m^2] and T is the temperature difference (T_i -T_o) in the direction of the heat flow, in this case between the inner and outer boundary of the insulation with the thickness b [m].

Samples of the insulation (about 0.1 x 0.1 m) were cut out and wrapped in foil to prevent moisture loss and were later examined in the laboratory with respect to **water content**. The volumetric water ratio was calculated from weight measurements of the samples before and after drying at 70 °C in the laboratory together with given values of the density. The gravimetric water content of the sand fill was also determined. Samples were taken every six months at a store temperature of about 70 °C in both heat stores.

5.5 HEAT TRANSFER CAPACITY OF THE GROUND HEAT EXCHANGERS

In order to study the heat transfer capacity of the ground heat exchangers, a simulation model was developed by Göran Hellström at the University of Lund (1996). The model contains a detailed description of the coupled thermal processes comprising heat transport through convection in the ducts and heat conduction in the ground. The model simulates 10 single U-pipes coupled in series.

The initial temperature of the ground and thermal resistance between the heat carrier fluid and the ground immediately outside the pipe are given constant values. The thermal properties of the ground are assumed to be homogenous and are calculated as a mean value of estimated values within the store volume at the current temperature level. Loading conditions are based on measured fluid values of inlet temperature and flow. With the aid of the simulation model, the outlet fluid temperature and thermal balance are calculated.

The thermal response test was performed by supplying the store with heat at a constant injection rate and by measuring the inlet and outlet temperature of the heat carrier fluid. Operation was set for a constant fluid temperature difference between the inlet and outlet of 5 °C. Prior to the test, heat was neither supplied nor extracted from the store in order for the fluid temperature to be representative of the mean temperature around the ducts. Evaluations of the heat transfer capacity of the ground heat exchangers were performed during the first year of operation of the heat store influenced by cyclic temperature. To check for temperature dependence in heat transfer capacity, response tests were carried out for two different temperatures, 35 and 60 °C respectively. Each response test lasted about one week.

Thermal response tests are more readily performed at normal temperature conditions in the ground. At elevated temperatures, heat losses during the response test have to be taken into consideration. The heat losses were estimated with the aid of the DST model (Hellström 1989). The DST (duct ground heat storage) model is commonly used for simulation of the thermal performance of ground storage systems. The model calculates the heat balance of a cylindrical heat store for different time periods under given time-dependent loading conditions. The calculated heat losses as functions of time were then submitted to the detailed simulation model.

The evaluation of the heat transfer capacity also included a sensitivity analysis with respect to estimated values of the thermal conductivity and heat capacity of the ground, initial temperature of the store, thermal resistance between the heat carrier fluid and the ground closest to the duct, and shank distance of the U-pipe. In addition, the development in temperature of the heat carrier fluid was estimated through an analytical solution of the heat conduction equation. A comparison with the analytical solution of the thermal response was made at steady-flux conditions. Steady-flux conditions are characterised by constant heat supply rate, resulting in unchanged temperature difference between the mean fluid temperature and local mean store temperature.

5.6 FLUID HEAT FLOW TRANSFER AND MEAN STORE TEMPERATURE

Supplied and extracted heat were measured inside the heat supply centre by heat flow meters in the fluid circuit. The heat flow meter measured the total flow in the fluid system, supply and return temperatures of the fluid taking temperature dependence of physical parameters such as density and specific heat into account, and continuously integrates the total heat supply for any time period. Transferred heat between the heat supply centre and the stores was then evaluated during charge and discharge periods.

The mean store temperature, T_m, was described in an empirical way as a function of the ground temperature in the centre of heat store No. 1, T_g. The ground temperature in the centre of the store was compared to the circuit fluid temperature during two separate weeks of the first year of operation when heat was neither supplied to or extracted from the heat store. The comparison was made for a centre ground temperature of about 40 and 70 °C, respectively. The empirical algorithm found is expressed as

$$T_m = (0.767 \cdot T_g) + 6.33 \qquad [°C] \tag{5.4}$$

For ground temperatures of 40 and 70 °C in the centre of the heat store, equation (5.4) results in mean store temperatures of 37 and 60 °C, respectively. The algorithm used is not compensated for the reduction in total heat losses with time after the first year of operation. A mean store temperature calculated in this way is therefore conservative for an operating period longer than one year. This is also supported by a few comparisons with results from DST computations. For various specific time points, corresponding to the first day of each cycle, the DST values showed on average 3 °C higher values than the calculated mean store temperature using the empirical formula.

During the initial heating of heat store No. 2, the same algorithm was assumed to be valid in spite of a different operational strategy in comparison with heat store No. 1. Furthermore, the steady-state mean store temperature was assumed to be 68 °C from the beginning of the second year of operation and onwards. The mean store temperature was interpolated between periods of initial heating (algorithm) and assumed constant temperature (68 °C).

Chapter 6.

Research results and evaluation

The out door temperature at the test field during the test period is shown in *Figure 6.1*. The out door temperature was continuously registered with eight values per day between February 1992 and December 1994. The annual mean out door temperature based on measured values was calculated at 8.5 °C for 1992 (February - December), 6.8 °C for 1993 and 7.3 °C for the year 1994.

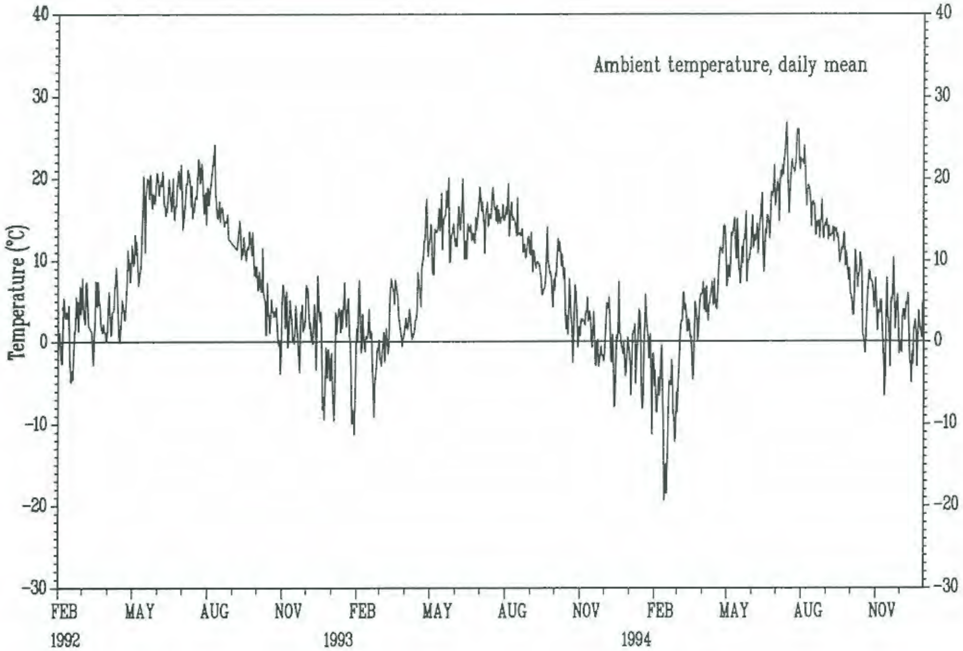


Figure 6.1 Out door temperature, daily mean values.

6.1 TEMPERATURES IN THE HIGH TEMPERATURE HEAT STORES

Heat stores No. 1 and No. 2 were put into operation in February and May 1992, respectively. In heat store No. 1, six heating cycles have been completed during three years. After a few months of initial heating, the mean ground temperature in heat store No. 2 has been kept just below 70 °C for a period of 2 years and 5 months.

Figure 6.2 shows estimated mean store temperatures in heat stores No. 1 and No. 2. For the total monitoring period, the mean store temperatures were derived at 44.8 °C and 63.8 °C, respectively using equation 5.4. The calculation was based on measured mean ground temperatures of 50.2 °C and 69.8 °C in the centre of heat stores No. 1 and No. 2, respectively.

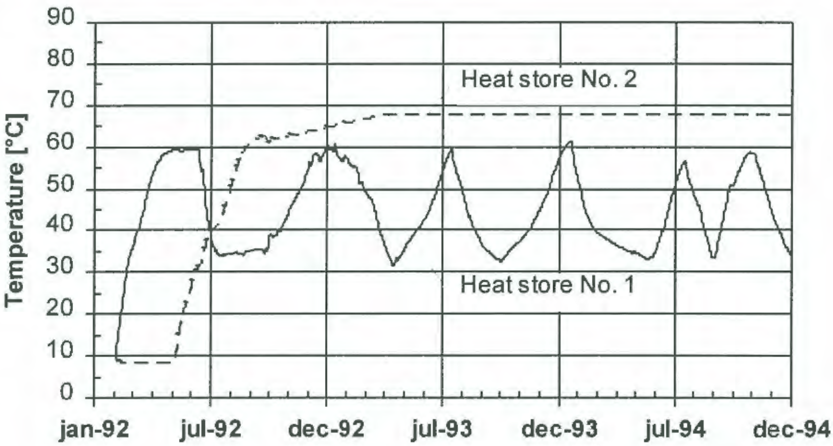


Figure 6.2 Mean store temperatures in heat stores No. 1 and No. 2. The mean store temperature was derived from equation 5.4.

In heat store No. 1, the supplied and extracted heat for the total monitoring period was measured at 378 MWh and 116 MWh, respectively. In heat store No.2, the total supplied heat was measured at 366 MWh. The rate of heat supply/extraction as well as the rate of storage temperature increase have been restricted for technical reasons, with respect to the capacity of the electric boiler and design store temperatures. The rated output (50 kW) of the electric boiler was utilised for one month during the initial heating of heat store No.1 (20 W/m duct). In this period, the ground temperature in the centre of the store increased by about 1 °C/day.

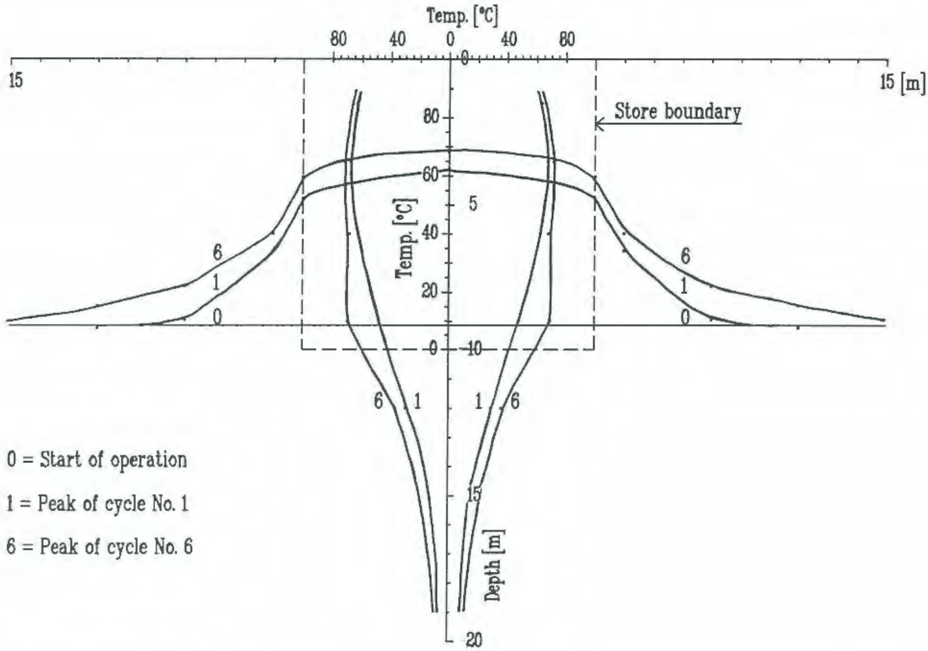


Figure 6.3 **Temperature distribution of heat store No. 1. The vertical distribution was measured in the centre and the horizontal distribution at 6 metres depth.**

In *Figure 6.3* the temperature distribution in store No. 1 is shown at the peak of the first and last cycle. The temperature within the major parts of the store volume was fairly uniform after the initial cycle. It started to diminish significantly immediately outside the store boundaries. The range of the heated zone outside the heat store exceeds 15 metres from the store centre at the peak of the last cycle, No. 6.

6.2 SETTLEMENTS AND CHANGES IN GEOTECHNICAL PROPERTIES IN CONNECTION WITH HEATING

Results - Settlements within the store volume

After about 2.5 years of operation, Store No. 1 with six heating cycles had settled 72 mm and store No. 2 with constant temperature had settled 88 mm. A comparison between the two heat stores shows that the settlements became greater at a constant high temperature than when the temperature was lowered in cycles, see*Figure 6.4*.

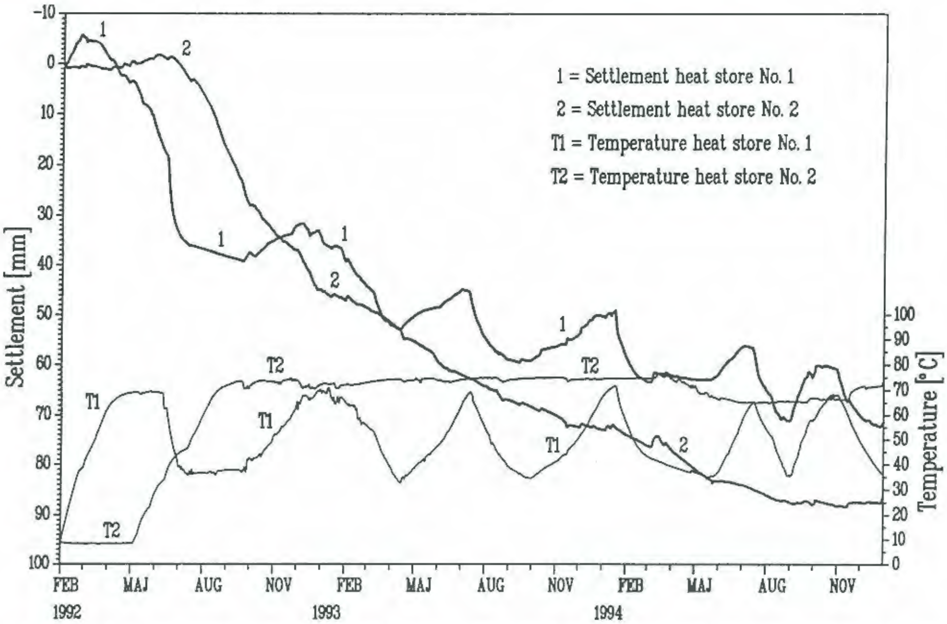


Figure 6.4 Development of total settlement and temperature in the centres of the heat stores.

Initially, a heave of the surfaces of the heat stores was measured in connection with the first heating period. After some time, settlements developed, initially at a relatively high rate of about 30 mm during the first three months. The rate of settlement then decreased with time. During the cooling periods in store No. 1 the temperature dropped and rapid increases in settlements were measured.

In the reference area, small variations of the natural settlement were measured with no clear trends.

The development of the excess pore pressure at 3.5, 6 and 9 metres depth in stores No. 1 and No. 2 is shown in *Figure 6.5* and *6.6*, respectively. Significant increases in pore water pressure were measured during the initial heating period from natural ground temperature to a temperature of about 70 °C in the centre of the stores. The magnitude of the maximum excess pore pressure increased with depth in both heat stores. In heat store No. 1 the maximum excess pore pressure was measured at 29 kPa and 58 kPa for 6 and 9 metres depth, respectively. The corresponding values in heat store No. 2 were measured at 34 kPa and 47 kPa. Negative excess pore pressures were measured in heat store No. 1 when the store was actively cooled and the temperature subsequently decreased.

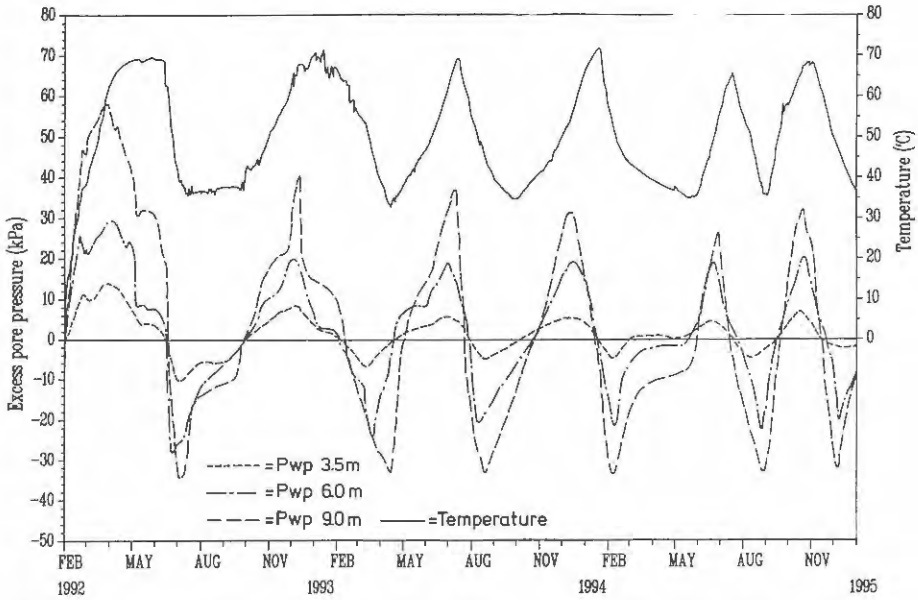


Figure 6.5 Development of pore water pressure and temperature in store No. 1. The pore water pressures were estimated from measurements with two complementary systems, electric piezometers and open standpipes.

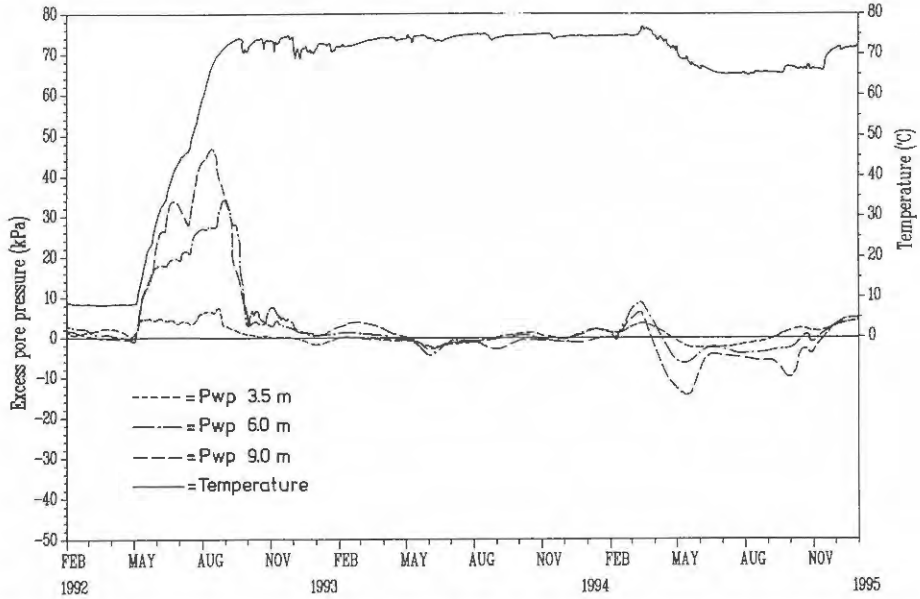


Figure 6.6 Development of pore water pressure and temperature in store No. 2. The pore water pressures were estimated from measurements with two complementary systems, electric piezometers and open standpipes.

A check of the pore pressure distribution in the store was made. The pore pressure was measured with piezometers positioned at various distances from a duct at 3.5 metres depth, see *Figure 6.7*. The highest value of the pore pressure was measured by gauge (1) in the figure, closest to a duct, and the lowest value of the pore pressure by gauge (3) at the greatest distance from a duct.

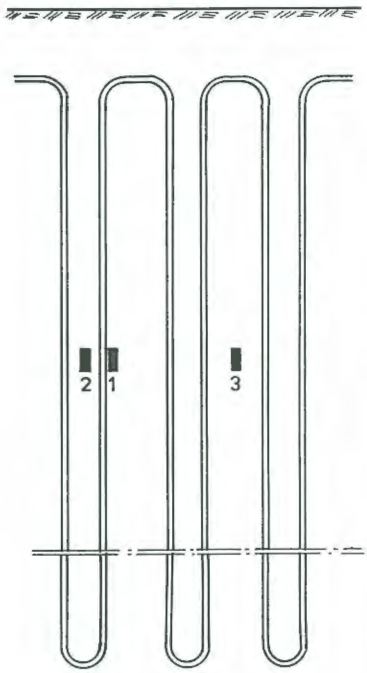


Figure 6.7 Location of pore pressure gauges for checking pore pressure distribution; in the centre of a ground heat exchanger (2), close to one shank of a ground heat exchanger (1) and between a pair of ground heat exchangers (3).

From measurements in the reference area, seasonal variations of the pore pressure were obtained, on average 2 kPa for depths between 3.5 and 19 metres.

The settlements measured on different levels at the edge of store No. 1 are shown in *Figure 6.8*. For a point at 2.9 metres depth, the settlement was eventually measured at 44 mm. The main part of the settlement in store No. 1 takes place between 3 and 9 metres depth. This soil layer consists of grey, slightly overconsolidated clay. Below 9 metres depth a small heave is noticeable. The developments in store No. 2 were similar to those in store No. 1.

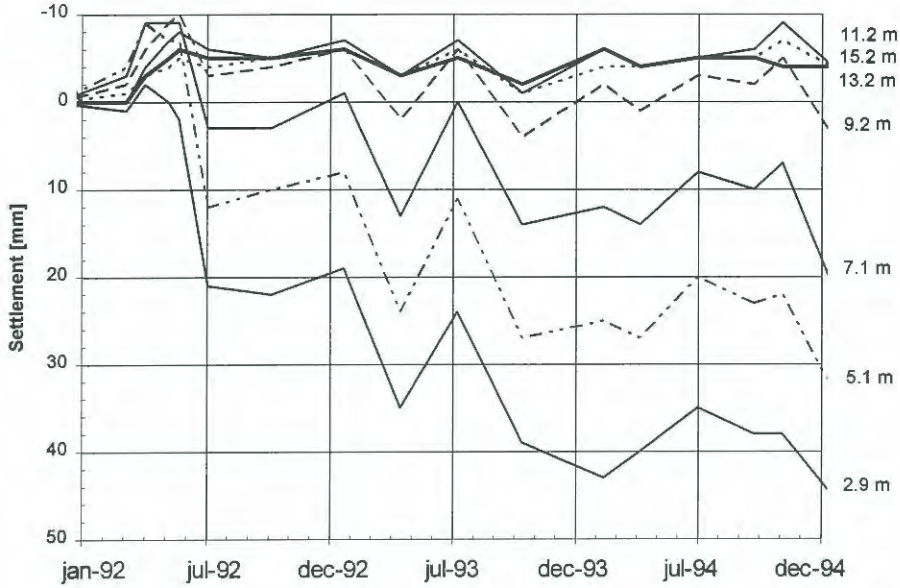


Figure 6.8 Settlements at different depths at the edge of store No. 1.

Results - Settlements outside the stores

The settlements were largest in the centre, somewhat reduced near the edges of the store and significantly smaller outside the store, as shown in *Figure 6.9.*

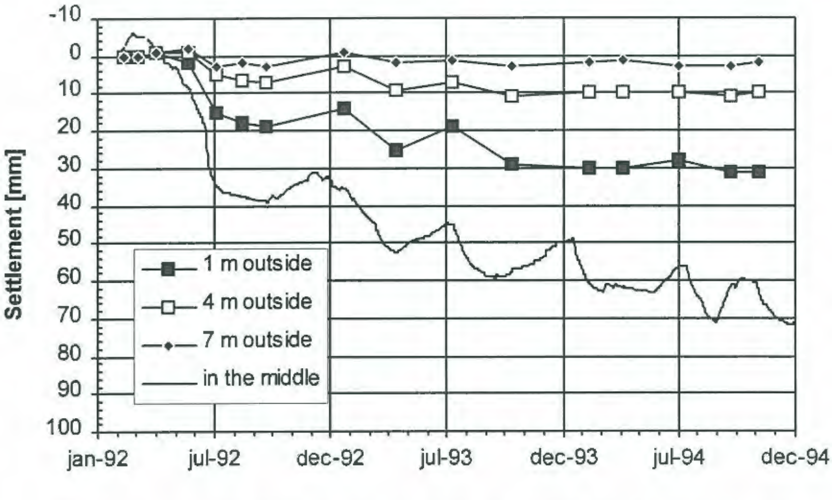


Figure 6.9 Settlements of the surface, inside and outside store No. 1.

The settlements outside the stores decreased with the distance to the stores. After 5.5 cycles in store No. 1, the settlement of the surface 1 metre and 4 metres from the edge of the store was measured at 31 mm and 10 mm, respectively. Furthermore, the measurements with horizontal hose settlement gauges showed a significant decrease of the settlements about three metres outside the edges of the stores.

Declining excess pore pressures were measured with increasing distance from the stores, *Figure 6.10*. The development of the excess pore pressure outside the stores was for the most part similar to the development of the settlements (and temperature).

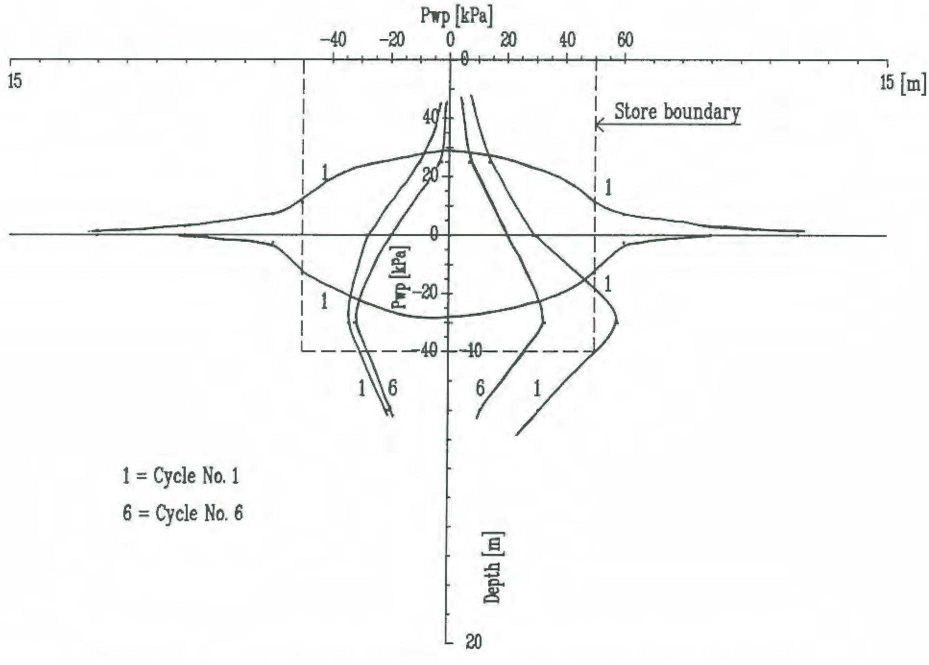


Figure 6.10 Distribution of excess pore pressure in Store No. 1.

Discussion

During the first heating period, the clay is subjected to a considerable temperature change of about 63 °C, which results in a significant reaction in the soil. The subsequent periods of heating give rise to temperature changes of only about 35 °C, which result in smaller reactions in the soil. Initially, the increase in temperature causes an increase of the soil volume due to thermal expansion of pore water and soil particles. A heave of the surface of the heat store may be expected.

When the temperature increases, an excess pore pressure is built up because of the difference in thermal expansion between water and soil particles and difference in expansion of the soil in the store and the surrounding soil. Undrained tests in a triaxial apparatus have been performed on soil specimens from 6 and 9 metres depth immediately outside the test field by Moritz (1995). The tests were performed by raising the temperature from 7 °C to 70 °C at a constant confining stress and resulted in excess pore pressures of 27 and 35 kPa for the specimens from 6 and 9 metres depth. These values are significantly lower than the measured values in the test field, both in heat store No. 1 and No. 2. This difference in pore pressure generation is probably due to the fact that in actual field conditions there is an increase in lateral soil pressure against the surrounding soil, which increases the excess pore pressure still further.

The magnitude of the excess pore pressure most evidently depends on the rate of the temperature increase and the maximum temperature level. If the increase of temperature is slow, the increase of pore pressure will be subdued by the simultaneous equalisation of the pore pressure caused by the consolidation process. This phenomenon can be seen by comparing the first energy charges in store No. 1 and store No. 2. In store No. 2, the energy charge took place at a slower rate than in store No. 1, which resulted in a lower excess pore pressure.

The generated excess pore pressures dissipate fairly quickly even when the temperature is constantly high, as in store No. 2. This may be explained by

- Decreasing viscosity of the pore water at high temperatures. The viscosity will decrease by a factor of about 4 and consequently the permeability is increased by a corresponding factor, making it possible for drainage to take place more rapidly.

- High compression modulus in the soil.

- Possible drainage along the vertical ducts. However, the readings of pore pressure gauges show that there is no obvious drainage along the ducts. The highest value of the pore pressure was measured closest to the duct and decreased with increasing distance from the duct. The development of the pore pressure thus mainly follows the spreading of the temperature from the ducts.

- Possible effects of anisotropic permeability properties of the clay. Such effects on the dissipation of excess pore pressures would be small since the permeability of homogenous and normally consolidated clays does not differ significantly in the vertical and lateral direction.

The results show a strong reaction in the clay in connection with the first heating in which the change in temperature is largest. Subsequent heating cycles produce much smaller reactions of approximately constant size. This behaviour is clearly shown by the pore pressure changes in store No. 1, Figure 6.5, and the same trend can be observed for the settlements and the shear strength. From other heat stores where the development of pore pressure has been followed, the findings are that the excess pore pressure gradually decreases with the number of cycles, a development not observed in this particular case.

The excess pore pressure will start to dissipate, resulting in a consolidation process and settlements. The settlements in the heat store with fluctuating temperature, store No. 1, include effects of a reduction of the soil volume due to thermal contraction of pore water and soil particles. When heating of store No. 1 stopped and the store was actively cooled, the temperature dropped and actually caused negative excess pore water pressures. This is explained by thermal contraction of the pore water in combination with a fast cooling rate and a limited possibilty for the soil to suck up water. It can also be observed that the settlement that occurred during the cooling periods is of almost the same size as the thermal contraction of pore water and soil particles for the temperature change.

When the excess pore pressure has been equalised, the settlement still continues. This is most obvious in store No. 2. The continuation of the settlements when there is no excess pore pressure depends on creep effects.

In this test field, the size of the settlements depends mainly on the creep settlements. Normally, the development of creep settlements in clay starts at a stress level of about 80 % of the preconsolidation pressure. In this case, it probably starts at a lower stress level when the temperature is increased, alternatively the preconsolidation pressure may be decreasing. Both phenomena will yield the same result. The total settlements in the heat store with fluctuating temperatures are smaller than the total settlements in the heat store with constant high temperature. The reason is probably that conditions with high temperatures and ongoing creep processes have prevailed for a longer time in store No. 2. The temperature fluctuations in store No. 1 create intervals with excess pore pressure, during which the creep process temporarily stops.

The measured settlements at the ground surface are at the most 72 and 88 mm in the store with fluctuating temperature and the store with constant temperature, respectively. In a comparison with calculated settlements for heat store No. 1, average values of the measured settlements have to be used because the calculations do not take into account swelling/compression caused by volumetric expansion/ contraction of soil particles and pore water at temporary temperature changes. In this case, the maximum mean settlement was measured at about 67 mm (see Figure 6.4). The corresponding calculated settlement of heat store No. 1 is 66 mm (see Table 3.1). In heat store No. 2 the settlements were measured at 88 mm and calculated at 84 mm. Hence the comparison shows good agreement between measured and calculated settlements.

It is also interesting to compare the calculated consolidation settlements when the excess pore pressures had just been equalised with corresponding measurements. In heat store No. 1 the measured value is about 25 mm and in store No. 2 about 28 mm. These values are compared with the values in Table 3.1, where the consolidation settlement has been calculated at 30 mm for both heat stores. In this case, the creep settlement is thus found to be most significant. A calculation of the creep settlements after 20 years results in total settlements of 190 mm for the heat store with fluctuating temperature, which is most similar to a real store.

Thermal expansion in connection with heating could be expected to cause horizontal ground movements. However, the measurements of the horizontal movements at the side of the heat stores were found to be contradictory and unreliable. Direct conclusions based on interpretations of the results are not possible due to great uncertainty in the measuring accuracy.

Results - Geotechnical properties of the clay

Clay samples affected by the high temperature in the heat stores have been examined in the laboratory with respect to density, water content, liquid limit, sensistivity and shear strength. Samples taken in heat store No. 1 were allowed to cool down to about 20 °C before being tested in the laboratory, except for the last sampling where the temperature of the samples was about 45 °C. Samples taken in heat store No. 2 were cooled down to various degrees. The temperature of the samples was between 20 and 45 °C at the time of the laboratory investigation. The results of the laboratory tests on samples from heat stores No. 1 and No. 2 are shown in *Figure 6.11* and *6.12*, respectively.

The geotechnical properties in both heat stores are within the same ranges and the average values for equal depths are almost the same. The variations are small at all levels.

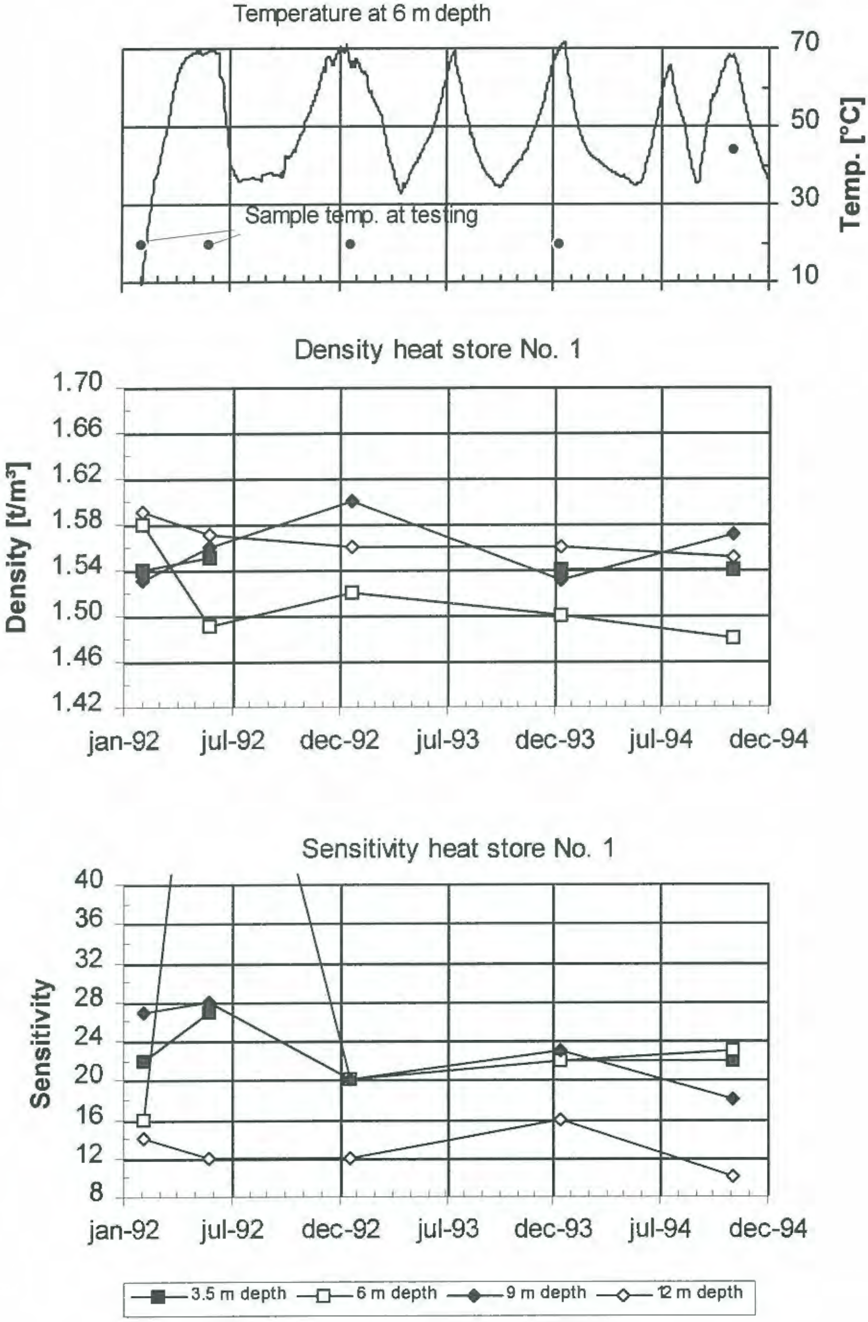


Figure 6.11 Density, water content, liquid limit, sensitivity and shear strength of clay samples from heat store No. 1, as a function of time.

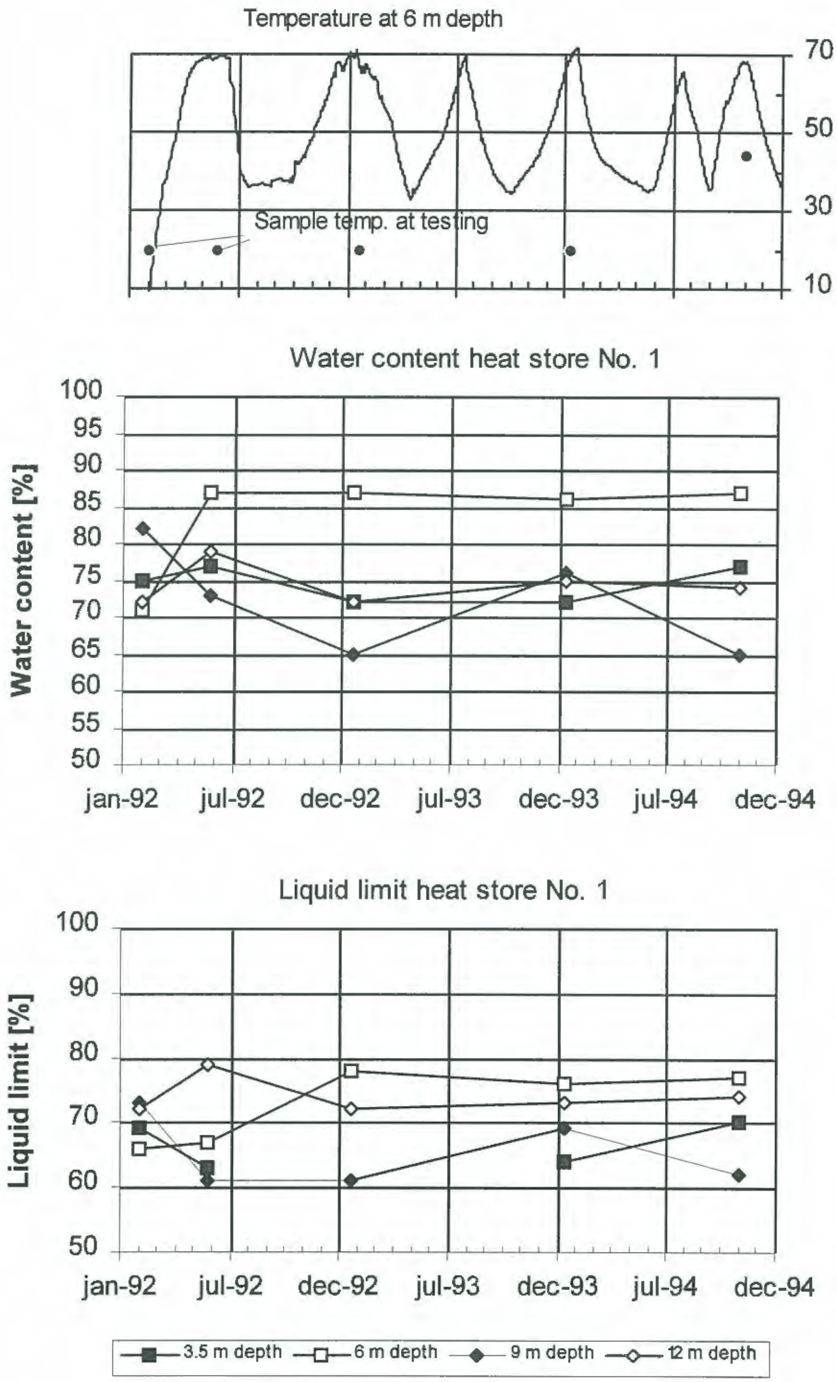


Figure 6.11 Cont.

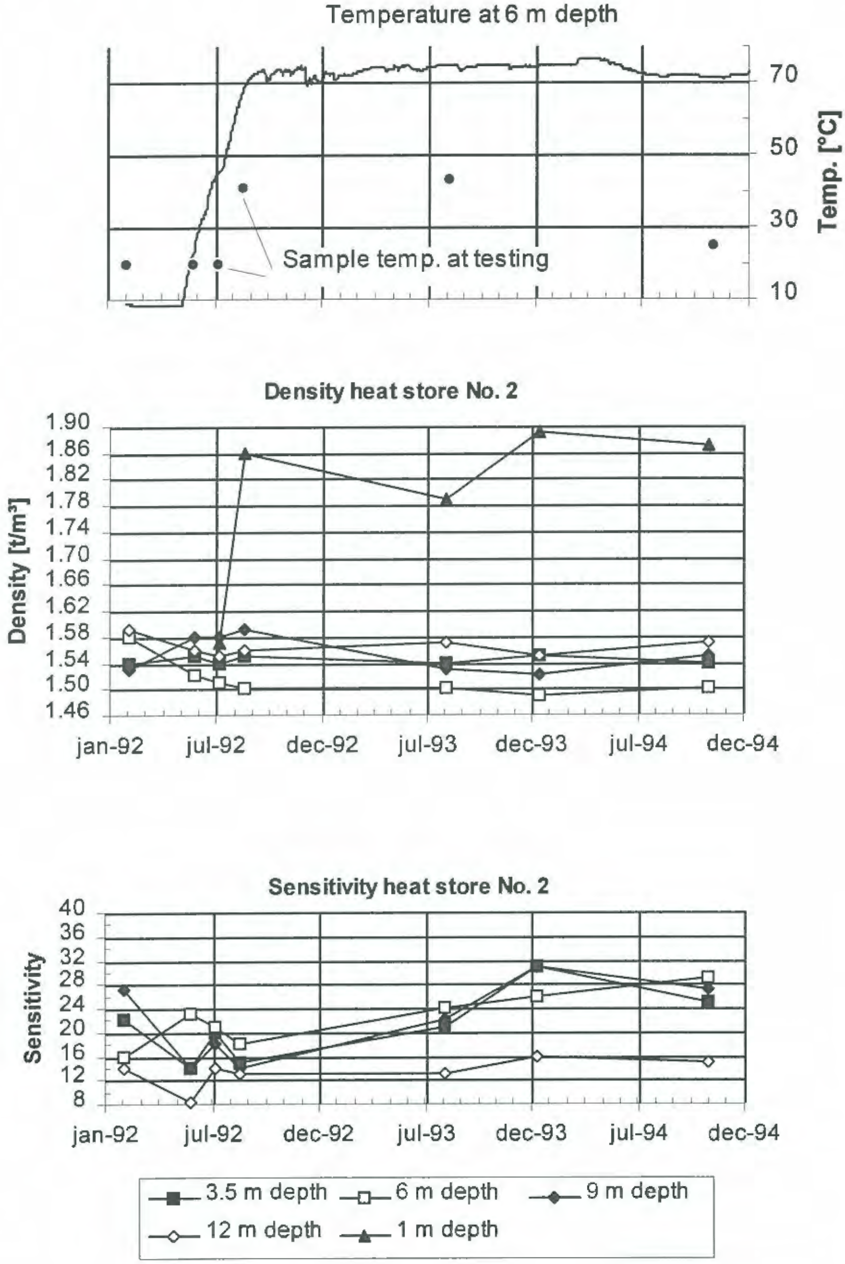


Figure 6.12 Density, water content, liquid limit, sensitivity and shear strength of clay samples from heat store No. 2, as a function of time.

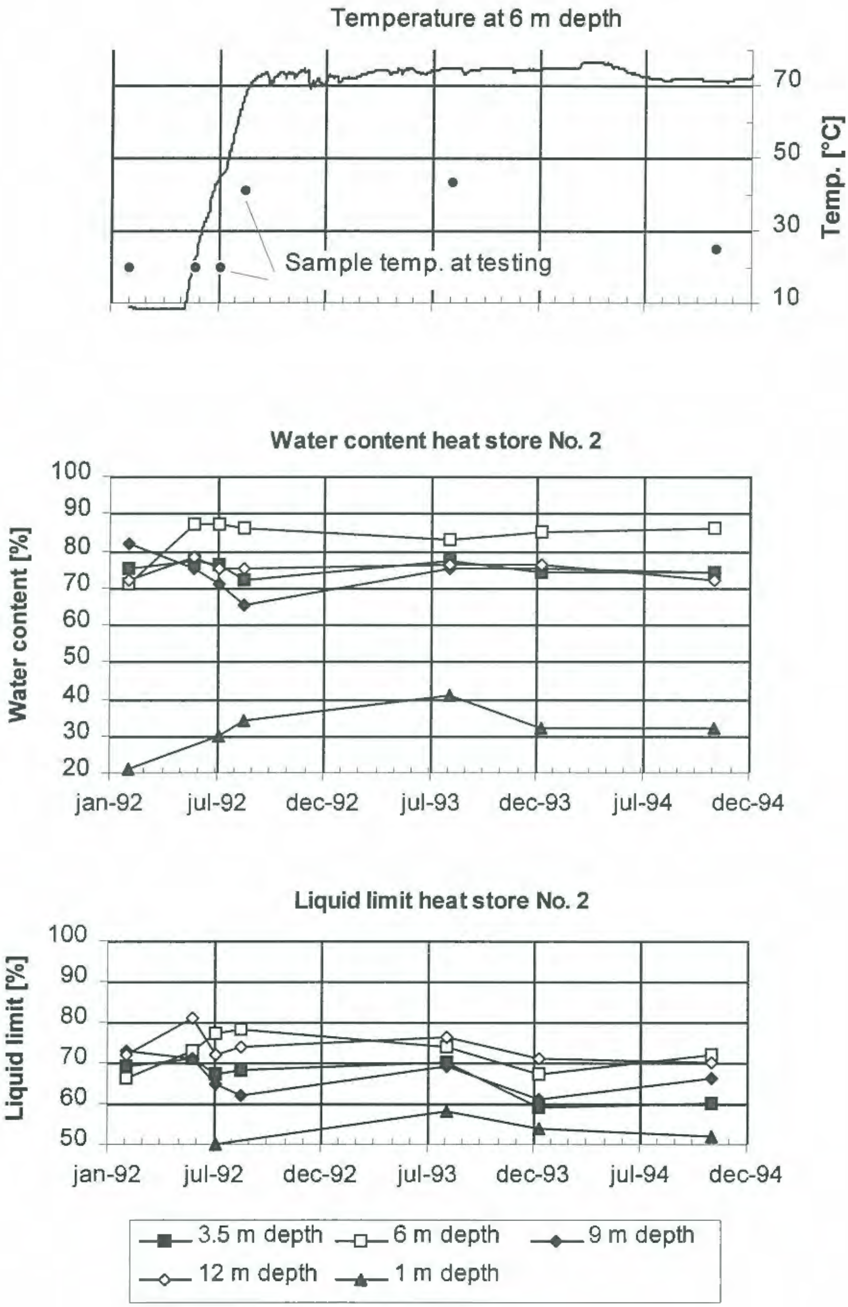


Figure 6.12 Cont.

Field vane tests and dilatometer tests for measuring the undrained shear strength of the clay were performed at different times and temperatures in the stores, *Figure 6.13*. Shear strength estimated from laboratory tests (fall-cone tests) is also shown in the figure. According to the test results, the shear strength of the clay was temporarily reduced at the first heating up of the stores.

Discussion

The evaluation is based on the results from three years of operation. The results have been compared to results from investigations prior to the construction of the test field. Measured variations of different geotechnical properties are the combined result of the resolution and inaccuracy of the investigation method used, natural variations of soil parameters and actual changes induced by elevated temperatures. The inaccuracy of the laboratory methods may be assumed to have a negligible influence on the variations. It is more difficult to distinguish thermal effects from natural variations. Effects of varying disturbances at insertion of in situ testing equipment and at sampling are difficult to estimate. Different temperatures of the samples in connection with laboratory testing also made the analysis more complicated.

Natural variations of different soil parameters can be described by using of the coefficient of variation, defined as the ratio between the standard deviation and the mean value. The coefficient of variation of various properties of the natural soil was calculated despite the somewhat limited number of samplings in the test field prior to the installation and operation of the stores. The coefficients of variation of the geotechnical properties in the test field calculated in this way were small and less than values normally presented in the literature.

Changes in geotechnical properties can be temporary or show a significant trend, increasing/decreasing, with time and/or with temperature and may eventually become permanent. Even if measured changes are within the limits of the natural variations, the measured variations may be a part of a long term decreasing or increasing trend caused by changes in temperature. Trends can be calculated on the basis of all the measured values or more simply estimated by comparing start values with end values.

The obtained variations are small for the majority of the studied geotechnical properties of the clay. It is possible that significant changes in geotechnical properties may appear after longer time periods than three years.

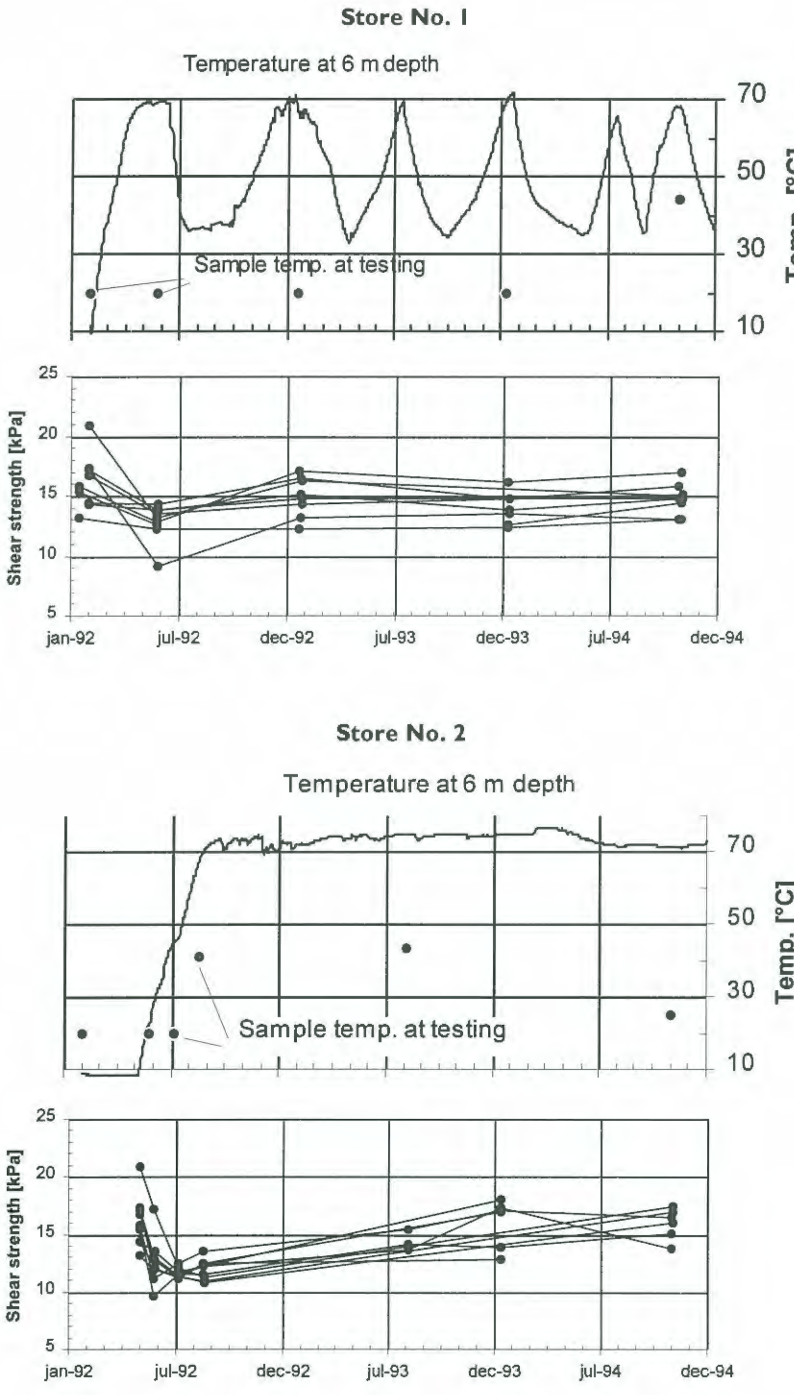


Figure 6.13 Results of shear strength tests in the heat stores (store No. 1 top and store No. 2 bottom).

Only small variations of the **density** have been measured in the heat stores. Possible changes because of volume changes are hidden within the natural variation.

Heating of the clay could be expected to cause some reduction of the **water content** through evaporation, especially at the upper levels of the stores, and water migration. Water migration from the stores when excess pore water pressure dissipates and the soil consolidates results in a reduced water content. A reduction of the water content of the clay is not confirmed in the test field. The measured variations are for the most part a result of natural variations: however, they do not exclude a long term influence of the temperature.

The measured settlements correspond to a decrease in water content of about 1 %. Such a small reduction, however, cannot be ascertained.

No clear trend of changes in the liquid limit was observed. Possibly, there is a trend of decreasing **liquid limits** with time in store No. 2 with constant high storage temperature. The liquid limit is a measure of the ability of a clay to attract and hold water. It depends on the mineral composition and the grain size distribution of the soil, possible organic matter and the concentration of dissolved salts and other compounds in the pore fluid. A change in liquid limit at constant temperature would thus be expected to be associated with a change in any of these properties.

Investigations have shown that the liquid limit decreases with temperature and that it is dependent on the viscosity of water (Youssef 1961). The kinematic viscosity of water decreases with increasing temperature. Heating reduces the strength of the bonds between mineral particles and water molecules and the bonds become looser (Tidfors 1987). This means that the consistency limit where the remoulded clay is transformed from a liquid state to a plastic state is lowered, i.e. the transformation takes place at a lower water content. This effect has only partly been observed in the laboratory tests because the samples were allowed to cool to various degrees before being tested.

Both in stores No. 1 and No. 2 the **shear strength** of the clay is temporarily reduced at the first heating up of the stores. In store No. 2 the decrease of the shear strength appears to follow the development of the excess pore pressure, see Figure 6.5. However, the results from store No. 1 do not allow this simple explanation to be readily applied because the pore pressures fluctuate with the temperature cycles. After the first cycle, the shear strength increased to about the same level as initial values prior to the operation of the store and remained at that level.

In the laboratory, triaxial tests and oedometer tests have been performed by Moritz (1995) in order to simulate the process of heat storage in this type of soil. Results from triaxial tests show that the undrained shear strength decreases with temperature by about 30 % when the clay is heated under drained conditions to 70 °C. Results from CRS oedometer tests show a similar decrease of the elastic compression modulus which describes the first part of the compression curve. (In normal conditions, this modulus is known empirically to be directly proportional to the shear strength.)

The conclusion is that the shear strength in this particular soil will temporarily decrease by about 0.5 %/C at the first heating. Similar effects comprising a reduction in the shear strength can be expected for other types of clays. This could affect the use of the top surface of the store and the surroundings and, if preconditions for stability problems exist, the stability of the ground.

6.3 TEMPERATURES, SETTLEMENTS AND CHANGES IN GEOTECHNICAL PROPERTIES IN CONNECTION WITH FREEZING

Consequences of alternate freezing and thawing of the clay surrounding the ducts in store No. 4 are shown in *Figure 6.14*. The store area eventually developed into an interconnected system of hollows partly filled with water.

Figure 6.14 Deformations caused by thawing of previously unfrozen soil. (Photo from January 1993.)

Temperatures measured in the freeze/thaw store are shown in *Figure 6.15*. The temperature was reduced to a minimum of about -1 °C. This temperature eventually caused freezing of the soil closest to the ducts. Freezing was noticed at the end of each freezing period by direct observations and checks with manual soundings.

The results are presented with a division of measured settlements of first time frozen clay close to the ground heat exchangers and measured settlements of the unfrozen ground between the parallel duct loops of ground heat exchangers.

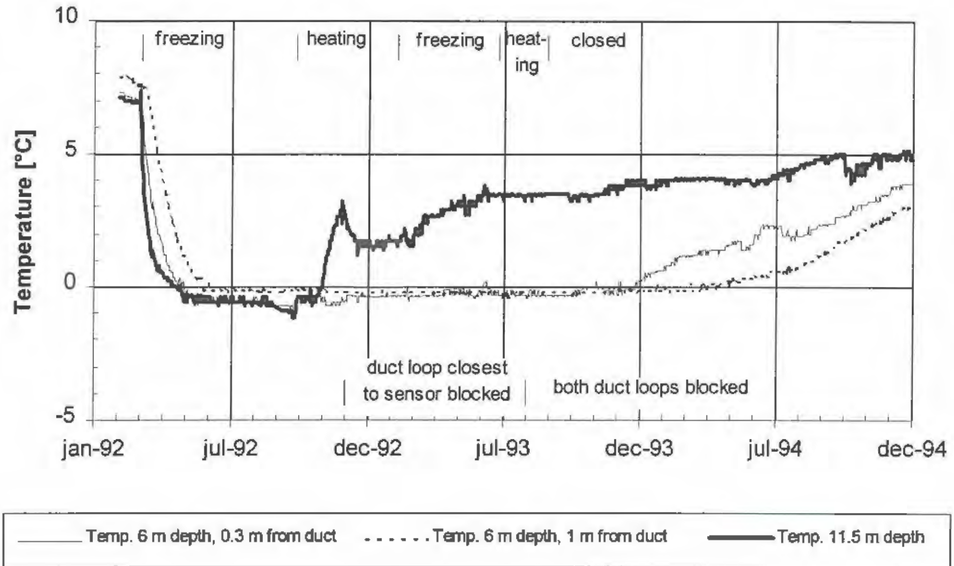


Figure 6.15 Temperatures in freeze/thaw store No. 4.

Results - Settlements measured in the frozen zone

The initial period of freezing caused a decrease of the ground temperature and a heave of the store was measured. Above the ground heat exchangers, the heave measured on average 84 mm at 2 metres depth and at about 58 mm at 5 metres depth.

During the initial freezing period, the pore water pressure was measured close to the duct immediately outside the expected frozen zone around one ground heat exchanger and below the store. When the temperature became close to 0 °C, a decreasing pore pressure was measured closest to the duct.

During the following period of heating, large settlements occurred around the ground heat exchangers. The settlements at 2 metres depth were found to be 1.8 metres and at 5 metres depth 1.4 metres at the beginning of the thawing period, *Figure 6.16*. The soil began to thaw, which resulted in large deformations of the frozen soil. At first, cavities developed along the centre line of the ground heat exchangers in the store, where the heat carrier fluid was supplied. Then cavities gradually developed with increasing distance from the centre.

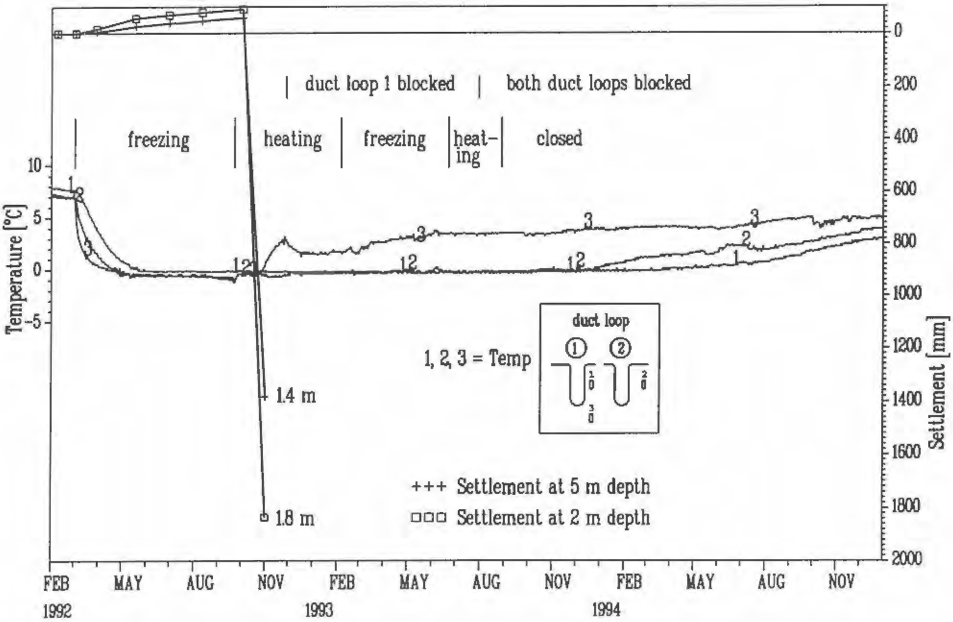


Figure 6.16 Settlements of frozen/unfrozen soil at 2 and 5 metres depth and temperatures in the store.

The top soil layer was intact, as well as the circulation in the ducts, during the initial stages of the heating period, but as the edges of the cavities began to cave in, the well rings of concrete in the upper crust sank into the soft soil and became covered by a mixture of clay and water. The depth of the cavities increased gradually and was measured at the most about 2.2 metres. The cavities then expanded and became more oval, following the position of the ducts, and shallower as the soil along the edges caved in.

Levellings along the parallel duct installation lines during the second freeze/thaw cycle showed that the depth of the cavities had been reduced and measured at the most 1.2 metres. The deformations during the first thawing period eventually resulted in one blocked duct loop (duct loop 1, see Figure 5.7).

The second freezing period started with a single duct loop in operation (50 % reduction of the storage capacity). The following thawing of the store was difficult to accomplish since the circulation in the remaining duct loop in the store gradually decreased. Consequently, the temperature increase in the store was slow. Final measurements after two freeze/thaw cycles, from levellings along the parallel duct loops, showed deformation depths of at the most 1.7 metres.

Results - Settlements measured in the unfrozen zone

At the end of the first freezing period, a heave of the ground between parallel loops of ground heat exchangers was measured at about 100 mm, *Figure 6.17*. Measurements of the vertical distribution of the settlements show that the heaving of soil took place in the upper 8 metres of the store. Small settlements were measured below this depth.

The pore pressure measured in the unfrozen zone increased during the initial freezing period. The pore water pressure was measured in the centre of the store between two loops of ground heat exchangers, but only during the initial freezing period.

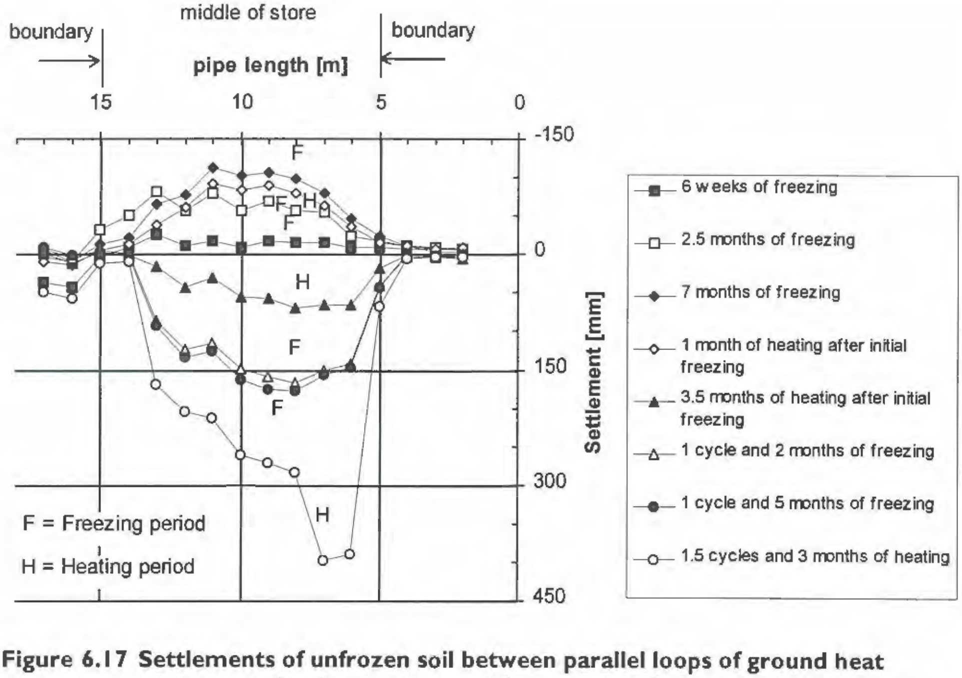


Figure 6.17 Settlements of unfrozen soil between parallel loops of ground heat exchangers (horizontal hose settlement gauge). The right part of the store functioned through two cycles, while the left part ceased to function after one cycle.

Settlements developed continuously during the subsequent thawing period and the second freeze/thaw cycle. The settlement process was temporarily reduced during the second freezing period. At the end, the settlements were measured at 0.4 metre in the central part of the store.

Discussion

Operating cycles with temperatures of the heat carrier fluid significantly below the freezing-point resulted in freezing of the soil. Ice lens growth in the clay starts and the amount of unfrozen water is gradually reduced when the temperature falls below the freezing-point. Free water in pores and cracks freezes first and ice lenses gradually develop owing to the extension of the freeze front. Freezing of the soil cylinder closest to the ground heat exhangers gives rise to an expansion of the soil volume as the pore water turns to ice. A heave of the frozen soil was observed as an effect of volume changes due to the development of ice lenses in the clay.

A larger heave was measured between loops of ducts than immediately above the ground heat exchangers. Since the ground between loops of ducts was only partly frozen, a heave of this area was expected to be less than that of the frozen soil. The volume increase of the entire frozen soil column close by may have exerted a pressure on the surrounding soil and thereby caused a heave.

An increase of pore pressure may develop in a zone immediately outside the frozen part because of volume changes in the frozen soil closest to the ducts. The increase may partly be subdued by a reduction of the pore water volume induced by a general decrease of the temperature in the store. At the same time, negative pore pressures (suction of soil water) are expected to develop in the frozen zone and at the freeze front as an effect of gradual growth of ice lenses at freezing temperatures. In general, the measurements during the inital freezing period support these assumptions.

Freezing of a soft clay completely destroys its structure. At thawing, water separates from the previously frozen clay. Thawing of the soil results in a slurry in which particles and clods of clay settle and eventually form a denser structure, leaving a free volume of water on top. In spite of being denser, the new structure has lost all previous preconsolidation effects.

The circulation of the heat carrier fluid had an obvious effect on the development of the settlements in connection with thawing. The cool liquid was circulated in the store starting in the centre, whereby the cooling effect diminished gradually on both sides of the centre line. Cavities developed beginning in the centre and gradually came to comprise the whole surface area of the store due to a continuous collapse of the pit walls.

The settlements of the previously unfrozen clay after thawing measured at the most 2.2 metres, corresponding to a relative compression of about 22 %. The size of the measured settlements corresponds well to predicted deformations of 25 % of the store (see Chapter 3.2). However, the deformations were assumed to comprise only a limited area with a certain radius around each ground heat exchanger, with fairly intact soil in between the ground heat exchangers. Instead, the deformations expanded to larger areas because the soil caved in to a much larger extent than expected.

Settlements of the area where the soil remained unfrozen developed continuously after the initial freezing period. The settlements are assumed to be dependent on random movements of adjacent collapsing soil on both sides and to some extent on temperature effects. Towards the end, larger settlements were measured at one side of the store. This reflects the gradual blocking and final cut off of the duct loop in this part of the store (duct loop 2, see Figure 5.7).

Results - Geotechnical properties of clay

Results from investigations in the laboratory with respect to density, water content, liquid limit, sensitivity and shear strength are shown in*Figure 6.18*. Following the reference sampling before establishment of the store, samples were taken outside the frozen zone after the first cycle of freezing and thawing and in the frozen zone after the second cycle. However, there were no significant changes in temperature during the second cycle. The thawing of the soil after the second heating period was therefore incomplete and small oval-shaped ice flakes were also observed in the samples from 9 metres depth.

In the frozen clay (February 1994), lower water contents and liquid limits were measured and compared with values obtained in the chilled unfrozen clay (January 1993). Results from fall cone tests in the laboratory also show lower values of shear strength and sensitivity in the frozen soil (February 1994) compared with the chilled unfrozen soil. From a comparison with the original soil at natural ground temperatures, the shear strength of the frozen soil is on average 40 % lower.

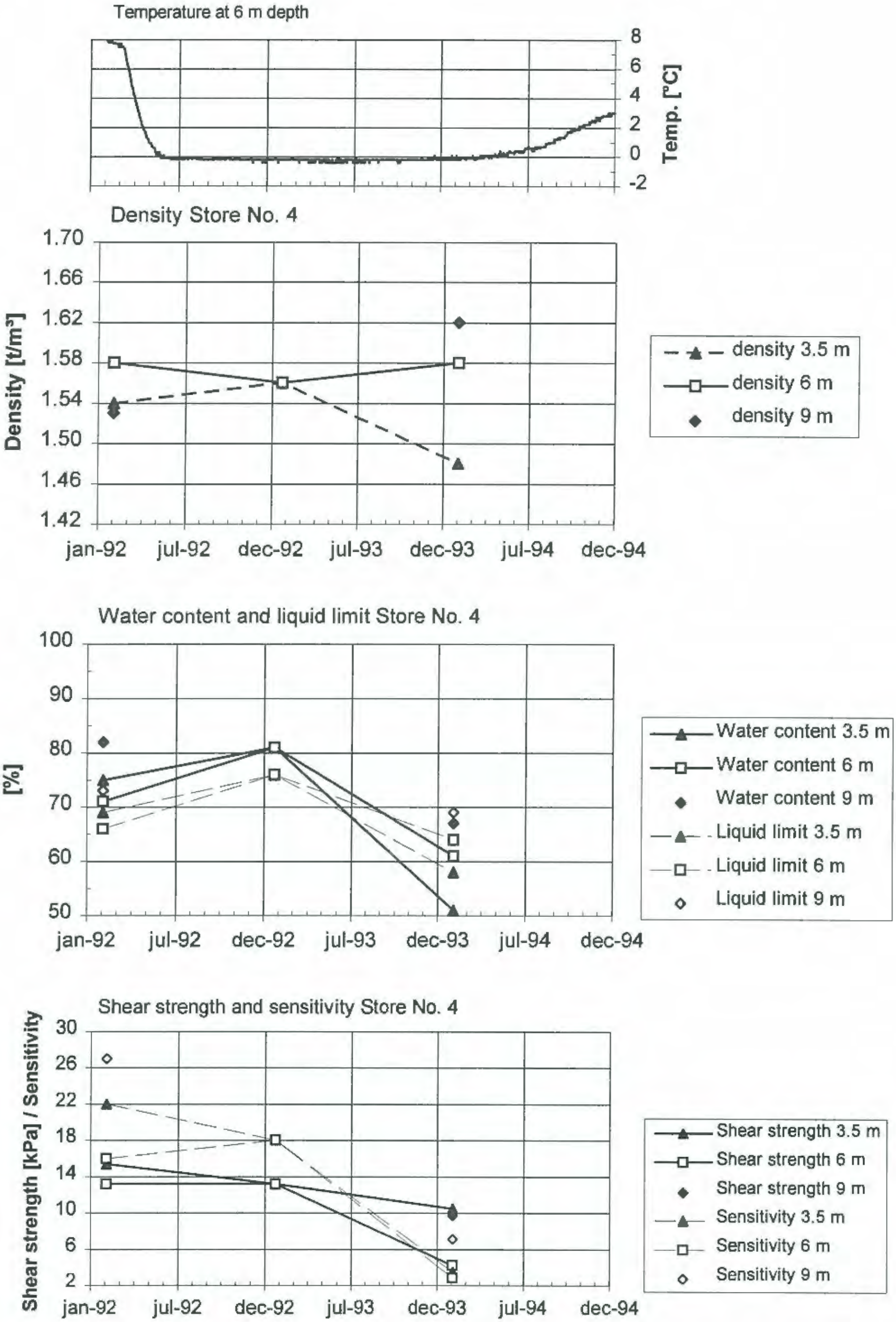


Figure 6.18 Density, water content, liquid limit, sensitivity and shear strength of clay samples from store No. 4, as a function of time.

Discussion
The freezing period was prolonged, but temperatures significantly below zero were never achieved in the store. The temperature gradient radially from the ducts was very small. This had obvious effects on the properties of the clay, in particular regarding water content, undrained shear strength and sensitivity. The thawing clay collapsed and underwent a process of water separation and reconsolidation.

The samples taken in January 1993 after the first freeze/thaw cycle were taken in unfrozen soil at a time when some heave possibly remained. Consequently, there may have been a small reduction in the measured **density**. The samples taken in February 1994 were taken in the frozen/unfrozen zone where large settlements had occurred and a significant densification was expected, particularly at greater depths. In general, the measured values conform to these expectations.

The **water content** was expected to vary in the opposite way as the density and this was also confirmed. There is no obvious reason to expect any changes in **liquid limit** and most of the measured changes may be related to natural variations in the clay. The very large settlements in the frozen/unfrozen soil may also have caused a significant redistribution of the soil particles with depth, which would have affected the liquid limits.

The reduction of the **shear strength** may partly be related to natural variations and thermal effects. The drastic reduction in February 1994 is likely to be an effect of structural changes in the clay. The clay had collapsed during the thawing process. This is also supported by direct observations of the clay samples and measurements of the **sensitivity**. With time, a reconsolidation process will give the thawed clay a more homogenous and denser structure. Its properties will be confirmed and some of the lost strength regained.

6.4 RANGE OF THE HEATED ZONE AND THERMAL PROPERTIES OF THE CLAY

Results - Range of temperature disturbance

The temperature was measured at 6 metres depth at the edge of the store and at different distances from heat store No. 1, *Figure 6.19*. The initial ground temperature was measured at about 8 °C. An increase in temperature was observed at 1, 4 and 7 metres outside this store, in which the temperature was cycled, after 1.5 weeks, 10 weeks and about 6 months of operation respectively.

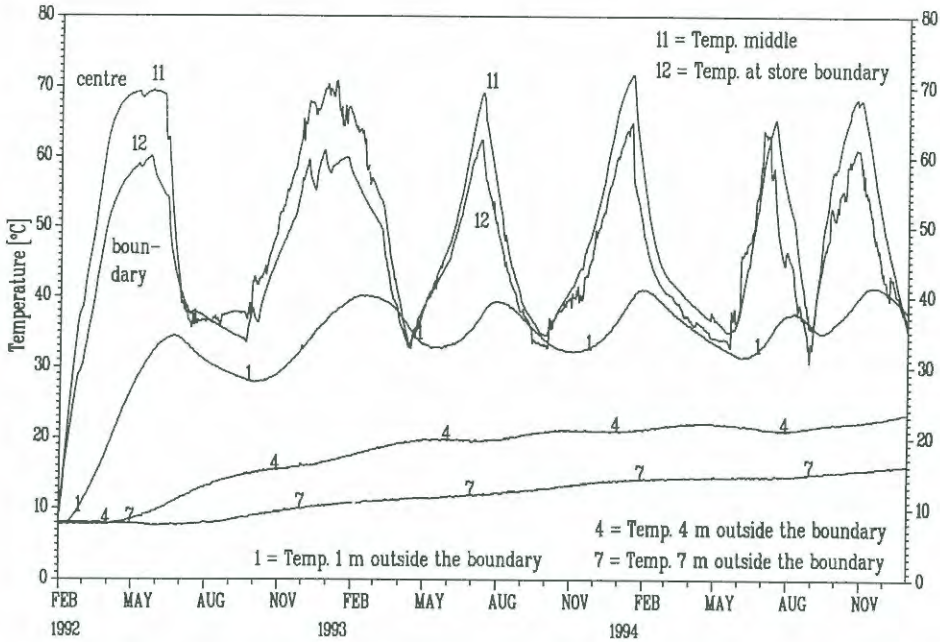


Figure 6.19 Soil temperatures at 6 metres depth in heat store No. 1, in the centre, at the edge of the store and at different distances from the store.

The temperature 1 metre from the edge of the store followed the temperature cycles with a small delay. The temperature in this point measured at the most 41 °C. After six operational cycles, each lasting 6 months, the temperature was measured at 23.5 °C and 16 °C 4 metres and 7 metres from the edge of the store respectively. A small tendency towards cycling of the temperature was noticed 4 metres from the edge of the store. The temperature 7 metres outside the store increased gradually without discernable cyclic variations of the temperature.

Discussion

A comparison between the measured temperature outside the heat stores and the temperature as calculated in Chapter 3.3 shows the calculated values to be somewhat higher at a distance of 1 metre outside the store, see *Figure 6.20*. Measured values of the maximum temperature, 41 °C, 23 °C and 16 °C at 1, 4 and 7 metres outside the store respectively show fairly good agreement with calculated values (45, 24 and 15 °C according to Chapter 3.3).

The result of the calculation is shown to be largely dependent on the distance to the edge of the store. The agreement between the measured and calculated temperature could be improved if the distance to the temperature sensor closest to the store was

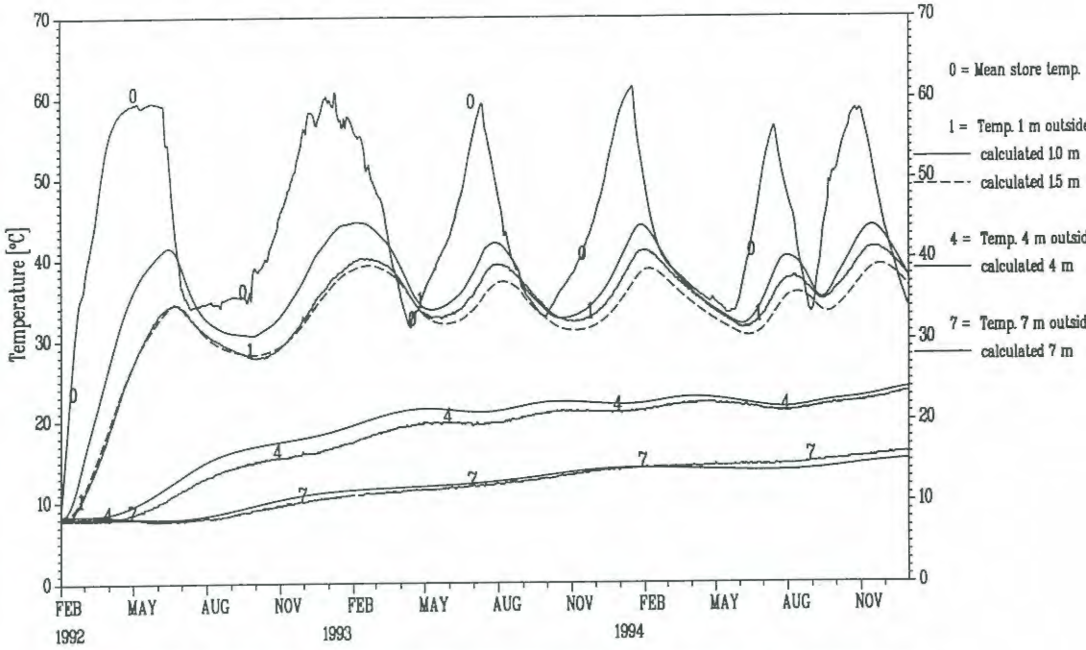


Figure 6.20 Measured and calculated temperatures at various distances from the edge of heat store No. 1.

assumed to be 0.5 metre longer than the theoretical value. This was found in both heat stores. The calculation is to a smaller extent dependent on variations of the thermal conductivity of the ground. For example, a change in thermal conductivity of ±10 % does not affect the calculated temperature more than ±1 °C. The calculations may be further improved by assuming an increase in thermal conductivity with temperature.

A comparison between the measured and calculated range of the thermal influence is shown in *Table 6.1*. The temperature beyond 7 metres outside the store had to be extrapolated in order to estimate the position of the temperature front. The measured temperature spread is somewhat less than the calculated values after every cycle, with the exception of the fifth cycle.

The calculations of the temperature spread involve certain simplifications. For example, the heat supplied to the stores during different modes of operation was approximated with mean values representative for one month, the shape of the store was approximated with a cylinder (∅ = 10 m) and the ground represented with a homogenous and isotropic material. Mean values of the thermal conductivity and heat capacity based on all values obtained at normal and elevated temperatures

Table 6.1 **Measured (extrapolation) and calculated values of the temperature spread (6 m depth) outside heat store No. 1 after each temperature cycle 35-70 °C.**

Cycle No.	Number of days	Measured extension [m]	Calculated extension [m]	Mean store temperature [°C]
1	210	8.2	10.5	45
2	227	10.0	11.2	48
3	168	11.1	13.1	43
4	213	12.5	12.6	43
5	123	13.8	13.7	42
6	121	15.4	18.0	47

were used, 1.03 W/m°C and 0.97 kWh/m^3,°C respectively. Some uncertainties may exist, particularly in the determinations of the thermal conductivity of the clay. Possible errors in the graphical extrapolation (beyond 7 metres) of the actual temperature spread also affect the comparisons with calculated temperature spread.

Results - Thermal properties of the clay

The thermal conductivity of the clay was determined both from computer calculations, where clay samples examined in the laboratory were used to obtain the input data in the form of volume shares of soil particles, pore water and pore gas, and from in situ measurements with a thermal probe. The thermal conductivity was investigated in heat store No. 2, which was operated at a constant store temperature.

Results from the determinations of the thermal conductivity are presented in *Figure 6.21*. The mean store temperature of heat store No. 2 is also shown in the figure.

Laboratory investigations of soil samples show that the degree of water saturation was close to 100 % below 1 metre depth. The porosity was about 0.7, except at the upper level, at 1 metre depth, where the porosity varied between 0.47 and 0.55 for the different samplings.

Results from the calculations show small changes in both thermal conductivity and heat capacity of the clay. The thermal conductivity of the clay below the upper dry crust is on average 1.0 W/m°C at natural ground temperature and 1.1 W/m°C at elevated ground temperature. The thermal conductivity at these levels varied

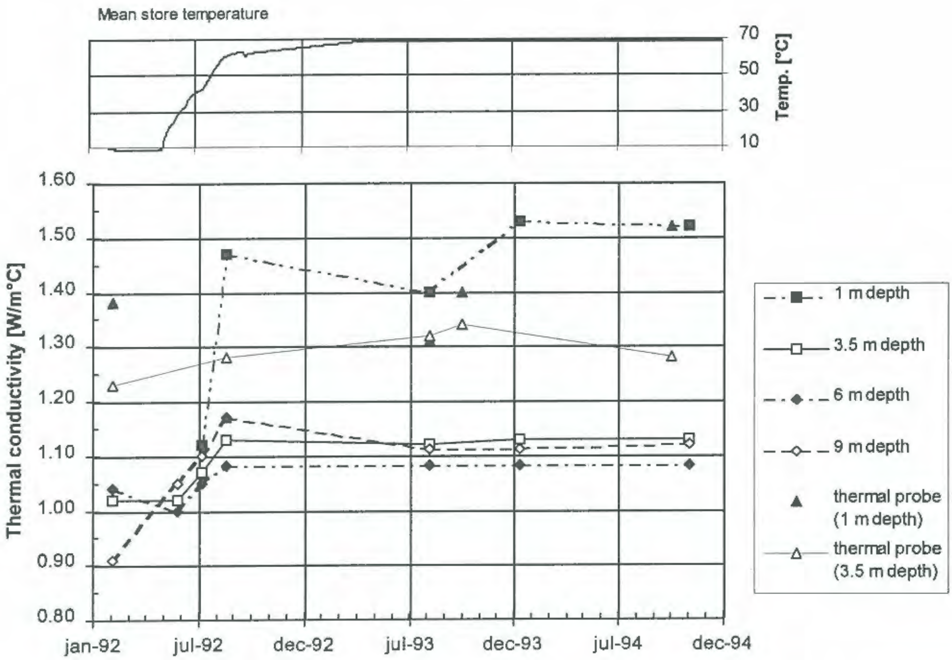


Figure 6.21 Calculations of thermal conductivity of clay. In addition, results from field measurements with thermal probe are indicated.

between 0.91-1.16 W/m°C over the whole range of temperatures. Measurements with thermal probe yielded thermal conductivities between 1.22-1.34 W/m°C at 3.5 metres depth. Larger values of the thermal conductivity were obtained at the upper level both as measured and as calculated.

Results from calculations of the heat capacity of the soil show small variations with no significant trends. The mean value of the heat capacity of the clay below the crust was calculated at 0.97 kWh/m^3,°C. For 1-2 metres depth, the heat capacity varied between 0.84 and 0.92 kWh/m^3,°C. For 3.5 metres depth and below, the heat capacity varied between 0.93 and 1.01 kWh/m^3,°C between the different samples.

Estimated values of the thermal conductivity and heat capacity of the clay versus depth, expressed as mean values, are presented in *Table 6.2*.

Table 6.2 **Thermal conductivity (λ) and heat capacity (C) of clay unaffected and affected by high temperature, determined by computer calculations with Condsoil and thermal probe in situ measurements.**

Clay at natural ground temperature (8 °C).			
Depth (m)	λ Condsoil (W/m°C)	λ Thermal probe (W/m°C)	C (kWh/m^3,°C)
<2	1.21	1.40	0.92
2-5	0.99	1.31	0.98
>5	0.98	-	0.99

Clay at elevated ground temperatures (68 °C).			
Depth (m)	λ Condsoil (W/m°C)	λ Thermal probe (W/m°C)	C (kWh/m^3,°C)
<2	1.47	1.43	0.86
2-5	1.12	1.31	0.96
>5	1.10	-	0.97

Discussion

There is a divergence in the results between the Condsoil values and values measured with the thermal probe. Values from computer calculations of the thermal conductivity are assumed to be more reliable. The reason for this is that the thermal conductivity is known to be largely dependent on the degree of water saturation and porosity of the soil. Since these parameters are almost constant, only moderate changes in the thermal conductivity could be expected, which is more in accordance with the Condsoil values. Furthermore, these values lead to more plausible results concerning the heat transfer capacity of the ground heat exchangers (Chapter 6.6). What may have caused the possible errors in the values measured by the thermal probe has not been clarified.

The results of the calculations for depths below 2 metres have shown a small trend of increasing thermal conductivity with temperature. Laboratory investigations have shown the volume share of soil constituents to be about the same irrespective of the temperature. The increasing thermal conductivity is therefore solely a result of increasing thermal conductivity of the soil constituents, mainly the pore water, during the initial heating period (see Figure 6.21).

The thermal conductivity for the dry crust at the upper level (1 m) varies because of different degrees of water saturation and porosities of the samples. No trends which could imply drying of the upper levels of the store have been observed. For the same reason, the variations of the heat capacity for the upper part are largely dependent on the varying degree of water saturation and porosity of the dry crust. For 3.5 metres depth and below, the degree of water saturation and the porosity were about the same for all samples.

6.5 THERMAL PERFORMANCE OF THE INSULATION

Results

The top surfaces of the heat stores were covered with two types of insulation material, giving a total thickness of 0.2 m. One half of each store was covered with expanded polystyrene (EPS) and the other half with extruded polystyrene (XPS). Each type of insulation was supplemented with a foil underneath to protect the insulation from moisture and limit the vapour diffusion from the stores. The values given by the manufacturers for the thermal conductivity are 0.036 and 0.030 W/m°C for expanded and extruded insulation respectively.

The results from measurements of the **thermal conductivity** of the insulation in heat store No. 2 with constant high temperature show a trend towards increasing values with time, both for extruded and expanded polystyrene, *Figure 6.22*. The calculated values are based on field measurements of temperature and heat flux through the respective insulation.

The initial values may include uncontrolled effects during construction of the heat store and unstable conditions during the initial heating. In order to quantify the deterioration, the measured end values were compared with the values given by the manufacturers. The results show that the thermal conductivity of the expanded and the extruded polystyrene increased by about 28 % and 24 % respectively during three years of operation.

Samples of the insulation were taken in store No. 2 and investigated in the laboratory with respect to volumetric **water content**. The investigations show that the water content of the insulation increased with time. The increase was in the same order for both types of insulation and the result varied from a few tenths of 1 per cent to several per cent. The increased water content was not obvious to the eye and the samples seemed dry on arrival at the laboratory, except at the surfaces.

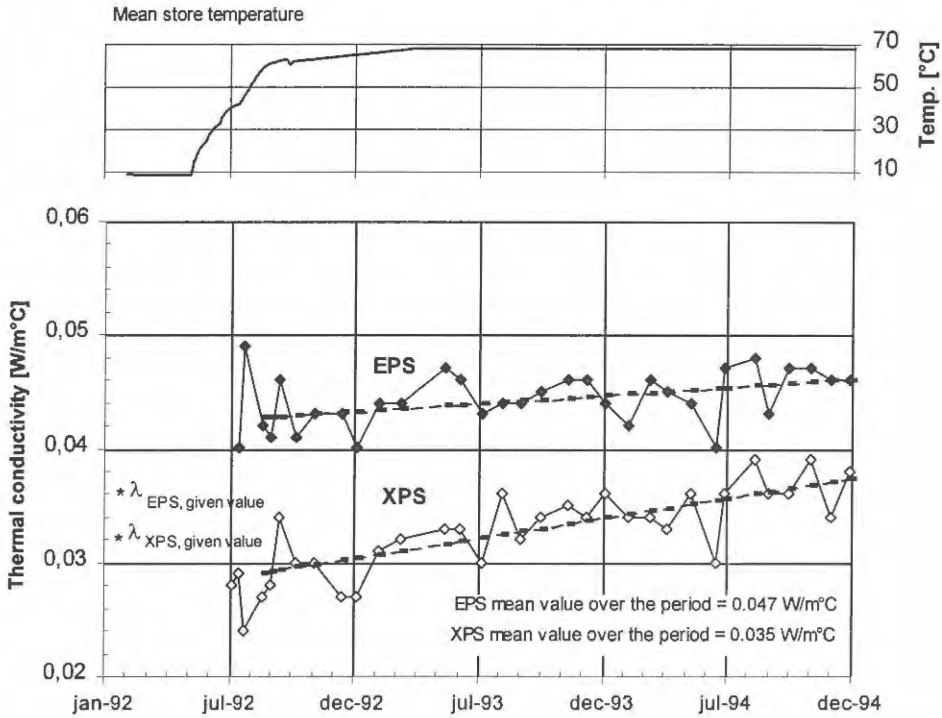


Figure 6.22 Measured thermal conductivity of expanded (EPS) and extruded (XPS) polystyrene on top of store No. 2.

Discussion

The obtained increases of the thermal conductivity are compared with what could normally have been expected. Values of the thermal conductivity for the insulation in practical use are supplied by the manufacturers and are given as 0.049 and 0.033 W/m°C for EPS and XPS insulation respectively. The method for determining these figures, however, does not correspond to conditions in ground heat store applications, which are characterised by long term effects of ground contact and vapour diffusion. A comparison shows that the measured thermal conductivity at the end of the evaluation period is somewhat higher than the given practical value for the XPS insulation and somewhat lower for the EPS insulation.

The thermal conductivity increases when the insulation is subjected to moisture, for example in the form of precipitation or by evaporation generated by the high temperature of the store, and by ageing in the case of extruded polystyrene, i.e. replacement of insulating propellant gas by air. Laboratory investigations of insulation samples also showed that the water content increased with time. The moisture uptake increased because of high temperature gradients (high vapour pressure gradient) between the store and the surroundings, which may explain the somewhat higher than expected increase in thermal conductivity for the extruded insulation.

An important factor to consider in the choice of insulation is the price. Larger deterioration of insulation properties for expanded polystyrene insulation compared to extruded does not automatically lead to the choice of the latter type of insulation since it is more expensive. With respect to the differences in investment costs and obtained increases in thermal conductivity, expanded polystyrene insulation may be considered more cost-effective than extruded polystyrene insulation.

6.6 HEAT TRANSFER CAPACITY OF THE GROUND HEAT EXCHANGERS

Results

The heat transfer capacity of the ground heat exchangers was investigated by performing thermal response tests in heat store No. 1 (Chapter 5.5). Comparisons were made with the aid of a detailed simulation model for calculation of the thermal balance. The thermal performance of the ground heat exchangers has been evaluated by Göran Hellström at the University of Lund (1996).

The results of the simulations are based on measured values from the response tests and estimated values of the thermal properties of the clay, thermal resistance between the fluid and the soil, and the shank distance of the U-pipes, *Table 6.3*. The thermal response test at 35 °C was performed during 8 days in September 1992 and the test at 60 °C was performed during 11 days in December the same year. Supplied heat was estimated at 6 MWh and heat losses at 1 MWh for the temperature of 35 °C. For the higher temperature level, 60 °C, the supplied heat was estimated at 9 MWh and heat losses at 4 MWh.

Thermal conductivity and heat capacity of clay at the specific temperature levels based on computer calculations with Condsoil were used for the simulations (Chapter 6.4). The thermal conductivity for the clay within the store volume was estimated as an average at 1.07 W/m°C and 1.11 W/m°C for the temperatures of 35 °C and 60 °C respectively. Corresponding heat capacity was estimated at 3.5 MJ/m^3K for both temperatures.

Table 6.3 Summary of data for the response tests at 35 and 60 °C.

	35 °C	60 °C
Duration of test [days]	8.19	11.21
Supplied heat [MWh]	5.89	8.73
Estimated heat loss [MWh]	1.1	4.0
Mean heat supply rate [kW]	30.9	32.4
Store temperature start [°C]	34.5	58.4
Store temperature end [°C]	39.3	63.2
Thermal conductivity of clay [W/mK]	1.07	1.11
Heat capacity of clay [MJ/m^{3}K]	3.5	3.5

The thermal resistance between the fluid and the soil immediately outside the pipe was calculated at 0.09 K/(W/m) (Hellström 1996). It includes thermal resistance between the fluid and the inner pipe wall and the thermal resistance of the pipe. Contact resistance between the outer pipe wall and the surrounding soil was assumed to be negligible. The shank distance of the U-pipe was assumed at 0.35 metre in accordance with the installation method used. It has not been verified that this distance is kept after removal of the tool.

Measured inlet and outlet temperatures together with calculated values of the outlet temperature at the investigated temperature levels are shown in *Figure 6.23* and *6.24*.

Discussion

The results show good agreement between the measured and calculated heat balance when estimated values of input parameters are used. The maximum uncertainty of the calculated heat balance is estimated at 5 %. Comparisons with analytical solutions of the heat conduction equation also show good agreement with the measured values.

Several parameters may influence the heat balance during a response test: the thermal properties of the ground, the initial temperature at the beginning of test, thermal resistance between the heat carrier fluid and the ground immediately outside the pipes, and the shank distance of the U-pipe. A sensitivity test shows that the greatest uncertainty is connected with the thermal conductivity of the ground, the initial temperature of the store and the spacing between the shanks of the U-pipe. Some uncertainties exist in the determinations of these parameters. The influence from uncertainties in heat capacity of the storage medium and thermal resistance between the heat transfer fluid and surrounding ground is small.

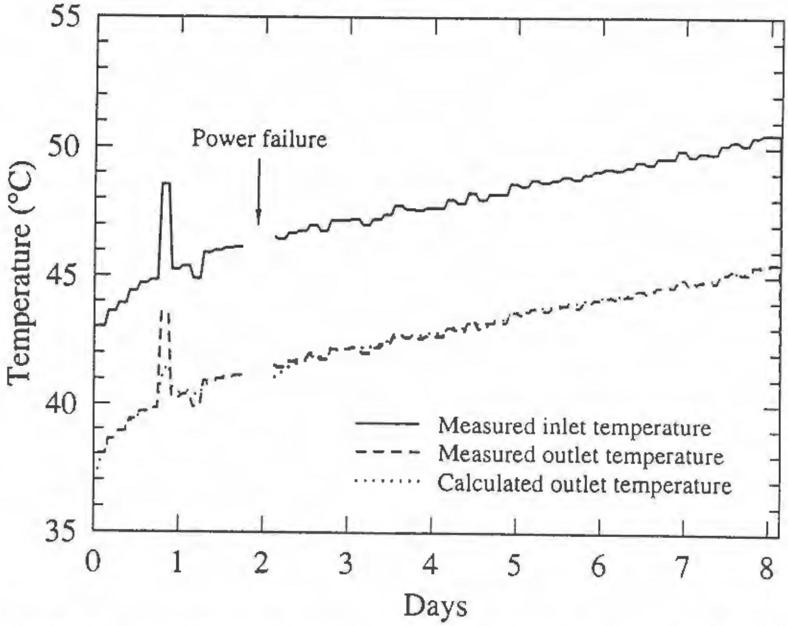


Figure 6.23 Result of thermal response test at 35 °C in store No. 1. Measured inlet and outlet temperatures together with calculated outlet temperature versus number of days since the beginning of the test.

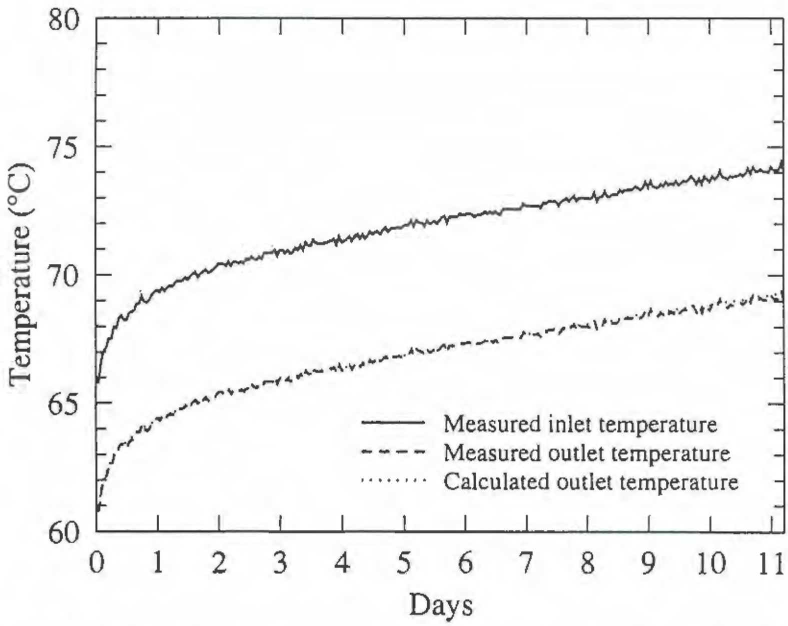


Figure 6.24 Result of thermal response test at 60 °C in store No. 1. Measured inlet and outlet temperature together with calculated outlet temperature versus number of days since the beginning of the test.

For the test at 35 °C, a ±10 % variation of the thermal conductivity resulted in a ±5 % variation in the injected heat at the end of the test. By assuming a parameter variation of ±1 °C for the initial store temperature, the injected heat varied at the most by ±7 %, *Figure 6.25*. Reducing the shank distance to 0.25 metre instead of 0.35 metre resulted in a 3 % reduction in the amount of injected heat at the end of the test. The variations in injected heat are in the same order for similar parameter variations at 60 °C.

The thermal response from single U-pipes as well as double U-pipes (Magnusson et al 1992) is well in agreement with applied theories and calculation models. An important assumption is that the heat transfer takes place solely through heat conduction. Furthermore, the thermal resistance between the outer pipe wall and the soil seems to be unimportant, which indicates that significant effects of a reduced water content close to the duct do not occur for the current temperatures and heat flows. In the estimation of operating performance of a duct heat store in clay, the thermal conductivity of the soil and the actual spacing between the shanks of the U-pipe after installation in the ground are associated with the greatest uncertainty in the field.

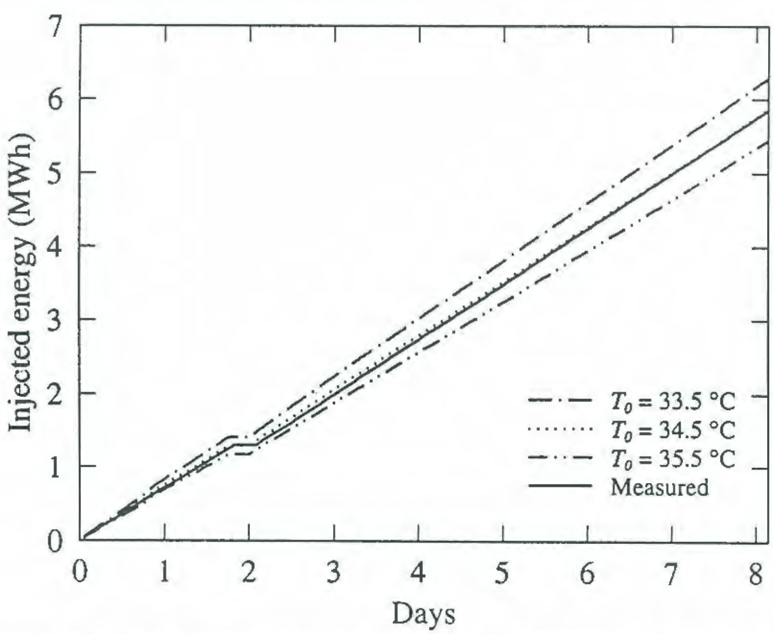


Figure 6.25 Result of thermal response test at 35 °C. Measured and calculated injected heat versus number of days since the beginning of the test. Variation of the initial store temperature T_0 (±1 °C).

6.7 HEAT LOSSES

Results

Heat transfer between the heat supply centre and the monitored heat stores was measured with the aid of individual heat flow meters in the fluid circuit, described in Chapter 5.6.

The measurements of transferred heat were used to estimate the transient heat losses from the heat stores. The transient heat losses will gradually approach steady-state heat loss during the long term operation of the stores. The absolute value of the heat losses for a cyclic heat store (heat store No. 1) is defined as the difference between supplied heat (378 MWh) and extracted heat (116 MWh) for a number of completed temperature cycles. The corresponding definition of the heat losses of a heat store, held under constant storage temperature (heat store No. 2), is the supplied heat (366 MWh) required to maintain constant storage temperature. The measured heat losses of the monitored heat stores are presented in *Figure 6.26*.

The measured steady-state heat losses are estimated at 9 kW for the cyclic heat store, No. 1, and 12 kW for heat store No. 2, held at constant temperature. A full transition of the heat losses to steady-state conditions appears to have occurred after about 20-25 months of operation.

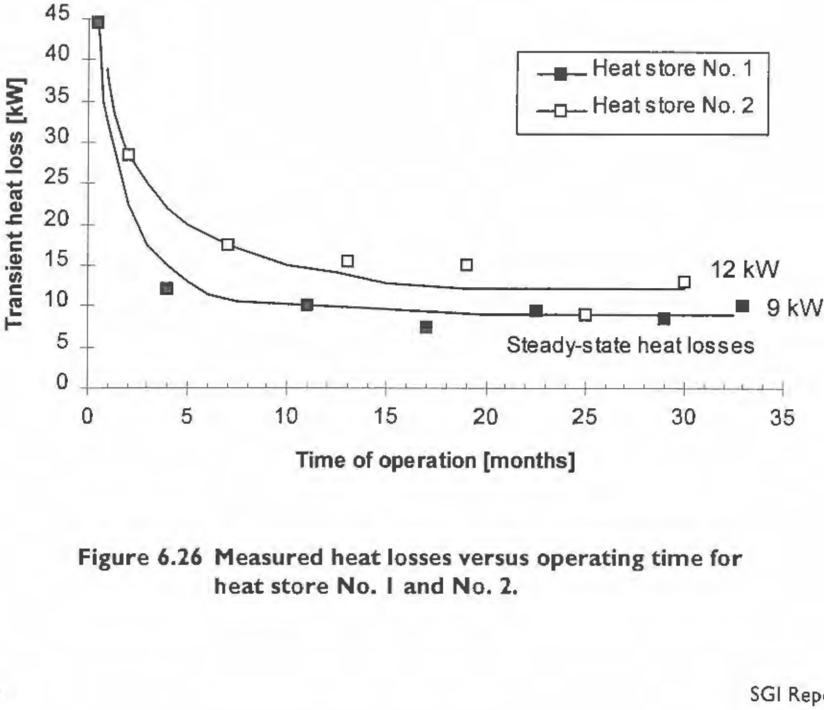


Figure 6.26 Measured heat losses versus operating time for heat store No. 1 and No. 2.

The relative transient heat losses can only be defined for cyclic heat store No. 1. The relative heat losses are defined as (1 - η), where η is the efficiency of the store expressed as the ratio between extracted and supplied heat for each completed temperature cycle. In general, the relative heat losses were high. On average, 70 % of the supplied heat was lost to the surroundings over the total monitoring period. The best cycle of six month showed a relative transient heat loss of 52 %.

Discussion

The steady-state heat losses have been calculated at 5.8 kW for heat store No. 1 and 9.1 kW for heat store No. 2, in accordance with Chapter 3.4.

A comparison between the calculated and measured steady-state heat losses is not readily made. The measurements of transferred heat in the fluid circuit also include heat losses from the distribution pipes between the heat flow meter in the heat supply unit and the heat stores, which are not considered in the calculations. The additional heat losses of the distribution pipes have been estimated from assumptions and simplified analytical calculations of the thermal resistance to be on average 1.5 kW for both heat stores.

By adding the estimated distribution losses to the calculated heat losses and then making the comparison, the measured steady-state heat losses are found to be about 25 % and 15 % higher than calculated values for heat stores No. 1 and No. 2, respectively. Explanations for the differences between calculated and measured heat losses are to be found both in the theory and the practical measurements.

In a sensitivity analysis, the response of the calculated heat losses in equation (3.19) was observed by single variations of physical parameters. Each sensitivity analysis was made for a parameter variation of ±10 % of the original value (Chapter 3.4). The response of the calculated heat losses is most sensitive, ±12 %, for a variation of the boundary temperature. Separate variations of the thermal conductivity of the ground and the heat loss factor affect the heat loss calculations by ±8 %. Variation in the insulation parameters has an impact on the results of less than ±2 %.

The estimation of the boundary temperature of heat store No. 1 with cyclic temperature was based on an empirical algorithm of the mean store temperature during the first year of operation (Chapter 5.6). During this initial year, the influence of the transient process is obvious and a significant underestimation of the average storage temperature is therefore possible. Heat store No. 2 was subjected to different operating conditions compared with heat store No. 1.

However, the same algorithm was used for the period of initial heating. From the beginning of the second year of operation, the average storage temperature was assumed to be six degrees below the maximum storage temperature, 74 °C in the centre. The validity of this assumption has not been verified.

Large relative heat losses were expected because of an unfavourable size and shape of the store, high storage temperatures and few energy turnovers. The thermal performance of the heat stores can be further improved by an optimised operating strategy based on reduced operating time at high store temperatures. This is obtained by reducing the idling time, between supply and extraction of heat, to a minimum. For a solar heating plant with a seasonal ground heat store of 35,000 m^3 the storage losses are expected to be in the order of 10-25 % of the heat supplied to the store (Gabrielsson 1997).

Chapter 7.

Operating results

The heat supply unit has been easy to manage and the test field has, for the major part, operated according to plan. The high temperature heat stores have shown good operating results. The measured settlements in the heat stores are quite moderate, less than 0.1 metre after three years of operation. So far, the obtained settlements have not damaged the ground heat exchangers. However, settlements, particularly in the form of creep, continue to develop.

The operation of the store with alternate freezing/thawing, store No. 4, was terminated after two cycles. Previously unfrozen soil in the store collapsed during thawing, which resulted in large settlements and eventually interrupted circulation in the ducts.

The equipment in the test field has in general performed satisfactorily. However, parts of the measuring equipment have shown poor reliability at high operating temperatures. The high temperature also made it necessary to adjust some of the procedures for measurements and investigations in the field.

7.1 OPERATING EXPERIENCE FROM THE HIGH TEMPERATURE HEAT STORES

Operation of the high temperature heat stores was started at the beginning of 1992 and continued satisfactorily throughout the intended monitoring period of three years.

Cooling of heat store No. 1 was provided by an inlet from a nearby river. Through an open system, river water was pumped to the energy supply centre. Initially, the pump seized and filters were frequently blocked by organic matter. An alternative solution with a closed system might have caused fewer problems.

After two years of operation, frequent leakages in the heating supply system temporarily reduced the reliability of the system. Investigations by Thierry (1994) showed that the problems occurred due to oxygen diffusion through the plastic pipes (PEX), where they were in direct contact with the heating supply system. The oxygen content activated corrosion processes, particularly at joints of carbon steel. Corrosion processes were also activated by the use of two different metals, steel and copper, in the pipe systems. The fluid was analysed and found to be corrosive through its ability to dissolve calcium (whereby a corrosion protective layer cannot develop on the metal surfaces). In the spring of 1994, heat exchangers were therefore installed in order to separate the heat carrier fluid in the ducts from the heat supply system. After this, no leakages or other interruptions of operation were observed.

The use of an uninsulated shipping container to accommodate the heat supply unit has necessitated extraordinary safety measures to avoid freezing damage during the winter season. However, freezing problems still occurred occasionally. An insulated building would have been preferable.

7.2 OPERATING EXPERIENCE FROM THE STORE WITH ALTERNATE FREEZING/THAWING

Store No. 4 began operation in March 1992. The inlet temperature was set to -10 °C with the aid of the cooling machine. Ground temperatures clearly below 0 °C were never reached during the prolonged freezing period. However, the freezing of store No. 4 became locally more extensive than intended due to difficulties in detecting the extension of the frozen soil around the ground heat exhangers. The device for detection of the range of the expected frozen soil (0 °C isotherm) around a ground heat exchanger proved to be inadequate due to the uniform temperature distribution. Temperatures close to the freezing point were registered by the sensors in the whole store, irrespective of the distance to the ducts.

The electric strain gauge piezometers, BAT, in store No. 4 functioned only during the first part of the initial freezing period and were then destroyed. The reason for this failure was probably due to the development of ice in the pipe, filter tip or transducer, although the measuring chamber of the transducer was filled with an anti-freeze liquid.

Large vertical settlements of about 2 metres appeared in parts of the store during the first thawing period, resulting in a reduced flow in one duct loop. The fluid flow was probably interrupted as a result of buckling of the ducts caused by settling soil. After the second freeze/thaw cycle the circulation in both of the ducts was interrupted, which made it impossible to continue operation. The store was therefore closed after two cycles of freezing/thawing and about 1.5 years of operation, *Figure 7.1*.

Figure 7.1 Store No. 4 after operation was concluded. (Photo from March 1994.)

The settlements in the store damaged the bellows hose settlement gauge and one piezometer in the centre of the store. The well rings above the ground heat exchangers and the settlement gauges inside the well rings sank and were eventually covered with clay. It was then impossible to carry out levellings of the settlement gauges.

Restoration

A desire to restore the ground area of a heat store installation may arise, for example because of recycling aspects, environmental reasons or alternative land use by the landowner. In January 1995, store No. 4 was restored. Installed ducts were removed from the store volume with the aid of an excavator. The removal of the ducts was performed, after removing the upper layer of the store, about one metre thick, by connecting the excavator bucket to the transition part of the duct between two pairs of ground heat exchangers, followed by pulling. It was possible to remove duct sections of up to 80 metres or four ground heat exchangers before tensile failure of the duct. The plastic ducts are deformed at removal and cannot at present be recycled with any commercial method. Normally, the ducts are burned after granulation. All ducts and installed equipment were removed from the store volume.

Due to buckling of the ducts, the heat carrier fluid could not be collected. The fluid was poured on the ground since the environmental effects of the calcium chloride are small. A normal procedure, with maintained circulation in the ducts, should include removal of the fluid by means of a compressor before pulling out the ducts.

7.3 SYSTEMS FOR INVESTIGATIONS AND MEASUREMENTS

Vertical and horizontal deformations

The automatic settlement gauges have functioned very well. The accessibility and accuracy are high.

The system for horizontal hose settlement measurements is sensitive to temperature variations. The measurements were performed with a continuous water flow through the hose in order to reduce the temperature differences along the pipe, but the accuracy was still reduced compared to steady temperature conditions.

Bellows hoses made of soft plastics, for measuring vertical distribution of settlements, were found to deform when exposed to high temperatures (70 °C) to such an extent that measurements became impossible.

Inclinometers are sensitive to temperature and a correction for temperature was therefore applied to the measured values. However, the results were still contradictory and unreliable.

Pore water pressure

Open groundwater pipes, of the KADO type, are resistant to high temperatures and the measurements are reliable. In the open plastic pipes, a delayed development of pore water pressure is measured which influences the evaluation, especially when the pore pressure changes rapidly. The time lag was estimated at a few days.

Electrical piezometers in long term operation at elevated temperatures have shown poor reliability. After about one year of operation several of the electrical piezometers had to be repaired or replaced. The pressure transducer or various electronic components had failed, probably because of the high temperature. It was laborious to maintain the existing system for automatic registration of the pore water pressure and it was decided mainly to rely on manual measurements in the groundwater pipes with some supplementary measurements of the BAT piezometers.

The high temperature caused a zero drift in the transducers and the zero value was therefore adjusted at intervals. Before reconnecting the transducer to the filter tip, the extension pipes were flushed clean from precipitate of rust and zinc oxide which appeared in the galvanised pipes.

Temperature

The temperature sensors in the middle of the heat stores, a total of six, were found to be damaged by moisture intake and were replaced after one year of operation. Damage to the connection cable and the casing of the Pt100 element may have occurred during installation or because of material defects. The new sensors, supplied with a more temperature resistant protective casing of the electrical cable and moisture protection consisting of silicone, were hung freely inside plastic pipes filled with bentonite slurry.

Automatic registration of the temperature was performed by measuring the voltage over the sensor in relation to earth. If moisture penetrated the sensor, the sensor came into direct contact with earth, which resulted in measurement errors. When the temperature was read manually from the instrumentation panel, this effect of moisture intake was negligible. Therefore, the automatic temperature readings were corrected with the help of manual temperature readings.

The development of the freeze-front around the ducts could not be observed with the special equipment described in Chapter 5.2. The reason why the 0 °C isotherm could not be distinguished was probably because the radial temperature gradient from the ducts was too low.

Field investigations

Samplings (standard piston sampling) and in situ tests (field vane shear and dilatometer tests) were performed in accordance with recommended standards, in spite of abnormal soil temperatures. The samples were tested shortly after transportation to the laboratory, about 7 km from the test field. However, the samples were allowed to cool down during transportation, which was assumed to have a minor effect on those geotechnical properties that were investigated.

The ground heat exchangers in the heat stores were theoretically installed at an equidistance of one metre. Points for samplings and soundings had to be located carefully in between. Some points were marked on the insulation during construction of the stores to facilitate subsequent field investigations. In connection with a field vane shear test in heat store No. 2, a duct was accidentally punctured by the vane. The loop with the damaged duct was disconnected.

Measurement system

Complementary systems for measuring settlements, pore water pressure and temperature facilitated the evaluation and prevented the use of erroneous values in the evaluation.

The plotting programme supplied with the logging equipment was not flexible enough for the current purposes. It should be possible to process the automatically collected data before presentation in diagrams and the layout of the diagrams should be variable for a uniform and clear presentation.

Chapter 8.
Conclusions, recommendations and future plans

8.1 CONCLUSIONS BASED ON APPLIED HEAT STORAGE IN SOFT CLAY

The test field comprising heat storage in soft clay in Linköping was in operation for three years. Experience and results from applied long term high temperature storage (35-70 °C) and alternate freezing/thawing in clay have led to the following conclusions:

Heat store design, construction and operational experience

• The improved duct installation method proved to be rational and fulfilled the expectations with respect to cost-effectiveness. The investment costs for a full-scale heat store (15.000 m^3) in soft clay with almost vertical ground heat exchangers were calculated with regard to experience from the construction of the test field at about 11 ECU/m^3 (12 USD/m^3) at the 1995 currency level. The total investment costs are divided into costs for design (15 %), ground heat exchangers (30 %), insulation (20 %) and machinery and installation (35 %).

• The heat stores have operated without any major problems. High operating accessibility is possible even if a single duct loop is damaged (one loop was accidentally broken by geotechnical installations). However, the capacity is diminished. Furthermore, consequences of oxygen diffusion through the plastic ducts can be eliminated by heat exchangers. With consideration to alternative land use, a heat store area in soft clay may be restored and the ducts removed without harmful environmental effects. It has been a major advantage for this research project to have an electric boiler for charging the stores as it provided a freedom for programming and facilitated the operation.

• The strain on electronic and plastic components is greater at extreme temperatures. Some sensors and measurement methods were shown to have insufficient ability to operate in long term high temperatures and freezing conditions. This problem could in many cases be solved by technical adjustment.

Geotechnical consequences of high temperature storage

- The geotechnical results after three years of operation do not imply any restrictions on ground heat storage in soft clay up to temperatures of 70 °C. However, long term impact has not been verified. For example, the ability of installed ground heat exchangers to withstand expected maximum settlements has not been demonstrated.

- An increase in temperature causes an expansion of pore water and the pore water pressure increases due to limited drainage. No substantial drainage was measured along the vertical ducts. The expansion of pore water causes swelling and the excess pore pressures create a consolidation process, resulting in settlements in the store volume. In addition to settlements due to the dissipation of excess pore water pressure during consolidation, settlements occur because of increasing creep effects. Creep settlements continue also after the equalisation of excess pore pressures.

- Settlements of the heat stores were moderate during the three years of operation and finally measured 72 and 88 mm in heat stores No. 1 and No. 2, respectively. The measured settlements are well in agreement with values calculated by using a settlement calculation model developed by Moritz (1995). The magnitude of the consolidation settlement is the same in both heat stores irrespective of different temperature strategies. Creep settlements are less in heat store No. 1 with a cyclic temperature variation compared to heat store No. 2 with a constant high temperature. The reason is lower mean temperature in heat store No. 1 than in heat store No. 2. Settlements, especially in the form of creep, continue to develop in the heat stores. The "final" settlement of the cyclic store after 30 years of operation is calculated at 190 mm.

- The settlement of a full-scale heat store with high annual cyclic temperature (35/70 °C), 15 metres in depth, in the same clay as in the test field is calculated at about 0.4 m after 30 years of operation. Settlements outside a heat store can be expected in the area where a certain rise in ground temperature appears. For a full-scale heat store with a store volume of about 15,000 m^3 and 15 metres in depth (vertical side of store), a temperature disturbance about 50 metres from the centre of the store could be expected after 30 years of operation.

- Changes in geotechnical properties such as density, water content and liquid limit of the clay in the heat stores are small and mainly within the range of natural variations. No significant reduction of the water content in the clay has been observed. Initially, a reduction in the undrained shear strength of the clay can occur. In a parallel study, laboratory tests have shown a 30 % decrease in the shear strength of the particular type of soft clay when heated to 70 °C (Moritz 1995). However, the field tests showed the reduction in shear strength to be temporary. The period of operation has been too short to determine possible long term changes in the geotechnical properties.

Geotechnical consequences of storage around the freezing point

- Freezing of previously unfrozen soft clay caused large settlements in connection with the subsequent thawing. The settlements amounted to about 2 metres or 22 % compression of the frozen depth. The settlements caused damage to the ducts in the store and circulation of the heat carrier fluid became impossible. The operation of a combined heat/cold store which includes freezing of soft clays that have never been frozen before is not possible with the design used here and must always be expected to be associated with major difficulties.

- At freezing, a pore water decrease develops, resulting in suction of water and eventually ice lens growth. Subsequent thawing results in a collapse of the soil structure, a separation of water and soil aggregates and transforming of the soil into a slurry. The clay particles and aggregates will then settle and free water appears in the upper part of the collapsed soil volume.

- The local effects of the freezing became more widespread. Thawing of frozen clay closest to the ducts was expected with fairly intact soil unaffected by freezing in between the ground heat exchangers. Instead, the settlements of the thawed clay eventually affected the whole area of the store. A large reduction in shear strength and sensitivity of the thawed clay was observed.

Thermal properties of clay and thermal performance of the insulation

- The range of the temperature disturbance from the heat store coincides fairly well with calculations both at short and long distances from the stores. The discrepancies may be a result of difficulties in determining the exact position of the temperature sensors at the measuring level. Furthermore, the comparison for greater distances from the store is largely dependent on a graphical extrapolation of the measured values close to the store.

- Small variations in thermal properties of the clay versus time and depth have been observed from calculations based on investigated clay samples. As expected, the thermal conductivity increased slightly with increasing temperature, below the dry crust from 1.0 W/m°C at natural ground temperaure to 1.1 W/m°C at elevated temperatures. However, the thermal conductivity evaluated from in situ measurements with a thermal probe was about 25 % higher compared to calculations with Condsoil. The calculated thermal conductivity is assumed to be more reliable. The reason is that the porosity and degree of water saturation of the clay were the same irrespective of temperature and therefore only small changes of the thermal conductivity more in agreement with the variations obtained with Condsoil are expected.

- Reduced insulating capacity of the insulation was observed. The deterioration was estimated at about 25 % for the total monitoring period, for the expanded and extruded polystyrene. The deterioration is greater than expected for the extruded polystyrene and somewhat lower for the expanded polystyrene with respect to available manufacturer information. In that sense, the heat store application involves tougher conditions which are more demanding than common applications in the building sector.

Heat transfer capacity and heat losses

- The thermal response from single U-pipes as well as double U-pipes (Magnusson et al 1992) in this type of soil under present operating conditions and temperatures may be accurately predicted by existing theories and calculation models. An important assumption is that the heat transfer solely takes place through heat conduction. The results show good agreement between the measured and calculated heat balance when the initial temperature, thermal conductivity of the soil and the shank distance of the U-pipes are closest to estimated values of those parameters. The maximum uncertainty of the calculated heat balance was estimated at 5 % (Hellström 1996).

- The measured heat losses are 15-25 % higher than the calculated values. The difference between calculated and measured heat losses is probably due to a conservative estimation of the boundary temperature. For steady-state heat loss calculations of ground heat stores, the following parameters have to be known: shape and size of the heat store, geological conditions, thermal conductivity of the ground and the insulation, thickness of insulation, temperature levels and operational strategy. Relative heat losses were determined at 70 % due to a large encapsulating area of the store in relation to its volume. For a full-scale heat store relative heat losses are expected to be 10-25 %.

8.2 RECOMMENDATIONS

Experience and results from construction and operation of heat stores in soft clay are promising and well-documented. However, a number of questions still remain to be investigated to gain a better understanding of the behaviour of ground heat stores in general and particularly in soft clays. Extensive programmes for research and development and operation/monitoring of pilot and demonstration plants with ground heat stores will on the one hand increase the knowledge and performance of seasonal heat storage and on the other hand stimulate a market for seasonal heat storage.

Some recommendations are made based on experience gained in this project regarding heat storage in soft clays.

Design and construction

- *Geotechnical investigation programme*

Design, construction and operation should be based on geotechnical know-how related to ground heat storage. If the geotechnical aspects are considered in the early planning stage of a building scheme, it is possible to improve cost-effectiveness. The most relevant questions forming a geotechnical investigation programme are location, design and construction aspects, heat losses during operation and impact on the store and the surroundings due to expected settlements induced by load, temperature changes and ground water flow. The effect of settlements in general increases with the system temperature why high temperature storage in soft clay therefore needs a more careful geotechnical analysis. Prior to the construction of a seasonal ground heat store, installation tests of ground heat exchangers are recommended at the actual site, in addition to conventional geotechnical investigations.

- *Location and possible use of the ground area*

In the initial study the geotechnical investigation should be focused on whether a proposed site is suitable for seasonal ground heat storage in general and specifically the type of heat store to be built. The location of ground heat stores in clay is primarily dependent on the thickness of the clay layer, the distance to surrounding buildings and a desire to minimise the length of the underground heat culverts. The clay depth also affects the installation depth of the ground heat exchangers and for a given storage capacity the required land area.

With respect to settlements, buildings and other sensitive constructions should be located outside the temperature influenced area around the heat store. Heat stores ought not to be located in slopes where even a moderate decrease in shear strength could lead to stability problems. In addition, the distance between a heat store and buildings, embankments etc. should be so great that the rise in temperature does not spread and affect their stability even in the long term.

The surface of the heat store can be used for recreation or other activities with low requirements on settlements, possibly with some adjustments of the ground surface area especially in the initial phase.

In connection with loading of the surface above and close to a heat store, particular attention must be paid to the fact that the undrained shear strength may be lowered by thermal influence so that stability is not jeopardised. It should also be borne in mind that the preconsolidation pressure may have decreased and/or the creep propensity may have increased, which would result in greater settlement than usual in the event of a load being placed on the surface.

- ***Heat store design***

In general, freezing with subsequent thawing of soft clay below the frost depth should be avoided in order to prevent substantial settlements and other damaging effects. The deformation damages the plastic ground heat exchangers, which makes the function of the store difficult to maintain. The loss of shear strength may also be very large and the usefulness of the area may be drastically reduced. Furthermore, the restoration of such a frozen and thawed area is difficult because of regenerated consolidation settlements.

The design of ground heat exchangers as well as the installation method should be adjusted to withstand expected settlement and compression in the heat store for the entire period of operation.

A cost-effective high temperature seasonal ground heat store design implies a 1.5-2 metre spacing between the ground heat exchangers and continuously installed ground heat exchangers in sections up to 250 metres. Each ground heat exchanger consists of a single or double U-formed duct (U-pipe), both of which are cost-effective. The double U-pipe is characterised by high heat transfer capacity. However, the great amount of tube makes the in situ installation somewhat complex. The single U-pipe is characterised by low investment costs.

Heat losses should be minimised through a careful selection of the most cost-effective insulation. For this particular seasonal heat storage application, the expanded polystyrene insulation proved to be the most cost-effective choice (investment/thermal conductivity) compared to extruded polystyrene insulation. The short vertical insulation of one metre at the sides of the heat stores seems to have been non-effective compared to an alternative solution with extended top insulation outside the store area.

To optimise operation and minimise the risk of corrosion by oxygen diffusion through the plastic ground heat exchangers, heat exchangers separating the sub-ground system from the rest of the distribution system should be used. An alternative is to use ground heat exchangers made of a diffusion tight material.

Research activities

- ***Monitoring of heat stores***

In general, the function of completed ground heat stores ought to be controlled and monitored as part of a scheme for operational control and feedback of generated results to the original predictions. In particular, prolonged operation of the test field is recommended in order to validate the settlement model and to determine the long term operational reliability.

- ***Effects of settlements on the ground heat exchangers***

The ability of the ground heat exchangers to avoid damage by settlements is of great importance in order to maintain the operation of a heat store. The limit of the ground heat exchangers may possibly be determined in practice at the test field by continuing current operation. Alternatively, measures could be taken to accelerate the settlement process. Possible detrimental effects of settling soil may be accounted for by developing alternative designs of the ground heat exchangers or measures to reduce the settlement propensity of the soil during the operation of the heat store.

- ***Clay subjected to temperature fluctuations***

The thermal behaviour of heat store applications is unique with respect to temperature gradients and moisture in the ground, operating conditions and thermal influence on soil properties. To obtain wider understanding and competence in this field, additional research and development is necessary. This should comprise studies in micro-scale of the behaviour of different clays subjected to elevated temperature as well as lower temperatures/freezing at various overconsolidation ratios.

Settlements of heat stores in typical Swedish clay may be predicted by the settlement calculation model developed by Moritz (1995). Further studies of the behaviour of different types of clays at elevated temperatures and in temperature cyclings are required.

The confirmation of absolute thermal properties in the ground and their dependence on temperature and time requires extensive efforts.

- ***Development of measuring methods and sample handling***

To increase reliability and avoid parallel measurement systems, the development of measuring methods and equipment adapted to high temperatures and moisture as well as freezing is recommended. To improve the accuracy of geotechnical investigations at high temperatures, evaluation methods need to be standardised and normalised with respect to conventional methods used in normal temperature conditions. Measuring methods should be evaluated for heat store applications in different geological conditions.

Quality assurance through development of systems for handling high temperature samples during sampling, transportation and laboratory investigation would improve and simplify the evaluation of geotechnical properties.

8.3 FURTHER OPERATION OF THE TEST FIELD AND FUTURE PLANS

The test field for high temperature storage will be in operation throughout 1997. The purpose is to make further studies of heat storage in soft clay at a higher temperature level, 90 °C, in heat store No. 2 and during a natural decline of the temperature from 35 °C in heat store No. 1. Geotechnical and thermal properties as well as operational reliability will be observed during the prolonged period of operation, which will enable the evaluation of possible significant changes.

Construction of a demonstration plant with a full-scale heat store is a natural development in order to verify the design and performance of high temperature storage in clay. The demonstration plant may consist of solar collectors connected to a duct store in soft clay for seasonal storage. For solar heating systems with seasonal ground storage, producing about 70 % of the total heat demand for 200 dwellings, the heating cost is estimated at about 130 USD/MWh (900 SEK/MWh) (Gabrielsson 1997). At present, this cost is not competitive in the Swedish market. The realisation of demonstration plants will therefore be dependent on possible subsidies and will also require commissions to be placed by clients.

The application of heat storage at high temperature has been investigated in a typical Swedish clay. Further investigations may be required in order to apply the results to other types of clay. Besides different types of clay, other geological formations of coarser or multi-graded material are common in Sweden and elsewhere. Knowledge of high temperature storage in clay may be transferred also to such formations. Development of more cost-effective ground heat exchangers as well as ground heat storage concepts for alternative geologies, assuming a positive assessment of the economic potential of these systems is desirable, as are measures for system simplification. The aim of the investigations should be to make a continuous study of the thermal and geotechnical impact on the ground in order to improve the design and performance of the store as an integrated part of a complete heating supply system and thereby reduce the overall heat cost.

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