XIII ICSMFE, 1994, New Delhi, India / XIII CIMSTF, 1994, New Delhi, Inde

CHANGES IN SOFT CLAY CAUSED BY INCREASES IN TEMPERATURE

CHANGEMENTS DANS UNE ARGILE SOUMISE A DES TEPERATURES ELEVES EN RAPPORT AVEC LE STOCKAGE DE CHALEUR

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SYNOPSIS: The development of effective energy systems non-hazardous to the environment has increased the interest in heat storage in the ground. High temperature stores enhance the possibilities of connecting energy systems without the need for a heat pump. The heat store can be supplied with solar energy or waste heat from industry. To be able to design a future heat store at elevated temperatures in clay, geotechnical properties and influence on the surroundings need to be investigated.

The paper describes a test field for high temperature storage and the simulation on clay samples by triaxial testing. Results are presented from in situ measurements of temperature, pore pressure, settlements and shear strength, as well as laboratory results from triaxial testing. The maximum temperature used is 70 °C, both in the field and the laboratory.

INTRODUCTION

Clay has proven to be suitable for storing thermal energy. A number of systems with a maximum storage temperature of about 35 °C have been built in Sweden.

A test field for high temperature storage in soft clay has been built in Linköping, Sweden. The test field was started up in February 1992 and will continue in operation for the next three years. The maximum temperature in the heat stores is 70 °C. Measured parameters are settlement, temperature, pore pressure and in situ strength of the soil.

The soil consists of two metres of solum clay on top of 6 metres of grey clay. Under the pure clay, the clay is coloured by sulphide for 3- 4 metres and overlies a varved clay with silt layers to a depth of 18 metres below the ground, Figure 1.

To gain deeper insight into the behaviour of warm clay, an extensive laboratory programme was also established. For this purpose, a standard triaxial cell was adopted, making it possible to generate and hold a temperature of 70 °C. Samples from 6 and 9 metres depth taken close to the test field were tested. The temperatures in the testing procedure were 8, 40 and 70 °C.

Mitchell and Campanella (1968) have carried out a great number of triaxial tests on clay at different temperatures. Results from undrained tests show that an increase in temperature in soft clay leads to an excess pore pressure which in turn leads to a certain swelling of the specimen. Clay particles and pore water expand when the temperature is elevated. Due to the difference in temperature expansion between clay particles and pore water, combined with low permeability, the pore water pressure increases. A theoretic model of the pore pressure change, Δ_u, is described:

$$\Delta u = \frac{\Delta T}{m_v}\left(\frac{w\rho_s(\gamma_s - \gamma_w)}{(1 + w\rho_s)} + \gamma_{st}\right) \qquad (1)$$

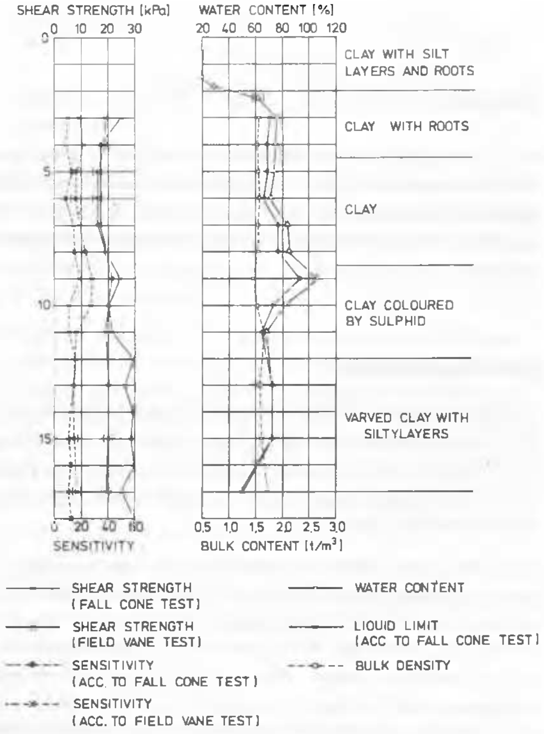

Figure 1. Geotechnical profile and characteristics of the test field.

where w is the water content, ρ_s is the compact density, γ_s is the thermal coefficient of expansion of mineral solids, γ_w is the thermal coefficient of expansion of soil water, γ_{st} is the physico-chemical coefficient of structural volume change caused by a change in temperature, m_v is the compressibility of soil structure and ΔT is the change in temperature.

TEST FIELD

The test field consists of two heat stores and a reference area. Each heat store has a volume of 1,000 cubic metres and is cubic in shape. Within each heat store, U-shaped ducts with a diameter of 25 mm have been pushed down to 10 metres depth and about 1 metre spacing, Figure 2. Each store consists of ten parallel connected duct loops, each comprising ten ground heat exchangers (U-pipes). The ducts are connected to a conventionally designed heat supply unit built into a shipping container. By circulating hot and cold water in the ducts, the surrounding soil is alternately heated and cooled. In order to reduce heat losses from the stores, the top surface and part of the sides are insulated with 0.2 metre of polystyrene foam with a diffusion proof foil at the bottom side.

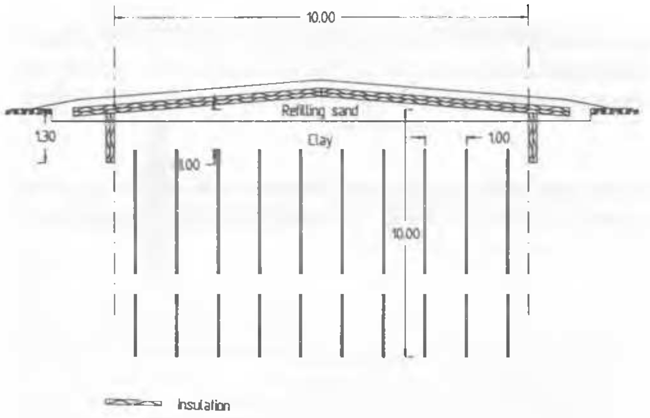

Figure 2. Store design.

In store No. 1, the temperature is varied between 35 and 70 °C, while in store No. 2 it is held constant at 70 °C. This procedure makes it possible to distinguish effects of temperature variations from effects due to the high temperature alone. The alternating store will be operating with two heating cycles per year.

Geotechnical Measurements

As a part of a larger scheme, changes in the geotechnical properties of clays are studied. The investigations are mainly carried out within a 4x4 metre surface in the centre of each store, where the influence of boundary effects is low. Instruments for measuring settlements, pore pressure and temperatures have been installed, Figure 3.

Investigations are largely focused on measuring settlements. Settlements are registered by automatic settlement gauges. Vertical distribution of the settlements is measured in bellows-hose settlement gauges. Settlements of the surface are also determined from levelling and measurements of a horizontal hose settlement gauge, often used for measuring settlements under embankments and footings. Understanding of the development of settlement also requires recording of pore pressure and temperature variations.

Pore pressure is automatically measured by pore pressure gauges (BAT) at three depths within the store, 3.5, 6 and 9 metres, and at one depth beneath the store, 12 metres. Pore pressure is also manually measured in an open system of ground water pipes, 13 mm in diameter. Manual measurements are carried out each month during the first cycle of heating and subsequently every third month. Temperature is automatically measured at the centre of each store and at specific distances from the store. The temperature and also samples of the clay are taken at corresponding depths where pore pressures are measured. Piston samples are taken three times during the first heating and subsequently every six month. Shear strength is evaluated from in situ measurements with field vane and dilatometer tests and from fall cone tests in the laboratory.

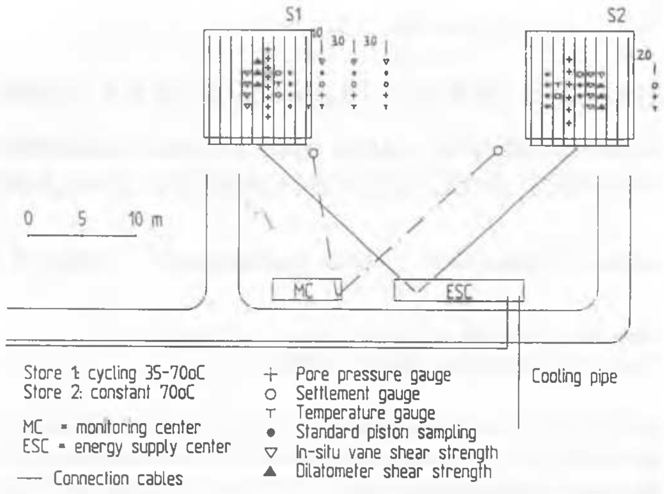

Figure 3. Instrumentation of the test field.

Results From In Situ Measurements

Results have been analysed for the first 7 months' operation of the test fields. Store No. 1 has completed its first cycle and store No. 2 has reached its maximum temperature of 70 °C. Heating of store No. 1 began in February 1992 by supplying the store with all the available effective power from the heater. This is reflected in a rather high gradient for the measured temperature. Designed maximum temperature was reached after 2.5 months of heating. The store was then supplied with energy to stabilise the temperature for a longer period of time. After 5 months' operation, the energy supply was closed. After one month, the temperature had dropped to 35 °C.

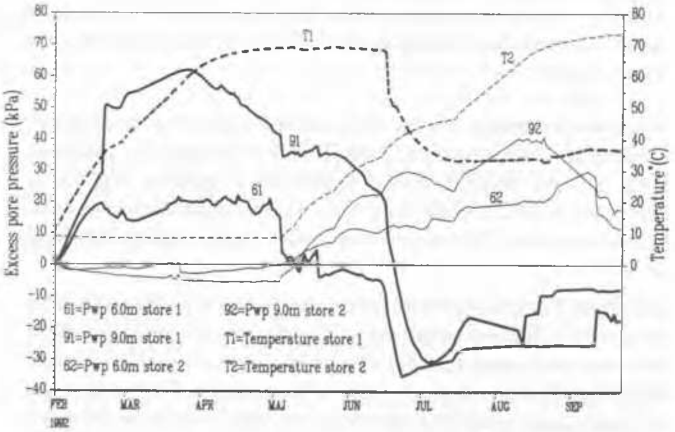

Figure 4. Development of temperature and excess pore pressure from the automatic BAT gauges.

Readings from automatic pore pressure gauges and open standpipes have been compared in order to obtain more accurate values. A direct comparison cannot be made when pore pressure changes rapidly, since the ground water pipes react more slowly. Figure 4 shows the development of excess pore pressure at 6 and 9 m depth. The pore pressure increased rapidly at the beginning and then began to decline. A maximum excess pore pressure of 20 kPa and 62 kPa was registered for 6 and 9 metres depth respectively. Pore pressure increased as long as the temperature gradient was high. Where excess pore pressure exists, the clay will begin to consolidate. The rate of consolidation depends on drainage conditions. When heating of store No. 1 was closed, the pore pressure decreased rapidly. The closing actually caused a negative excess pore pressure because of the declining temperature.

In order not to overload the energy supply unit, heating of store No. 2 started three months after store No. 1. Heating of store No. 2 was performed by gradually increasing input energy in four steps. The stepwise heating is shown in the temperature curve. The designed working temperature of 70 °C was reached after 3 1/2 months of heating. Pore pressure increased with temperature and the pore pressure co-varied with the temperature. Pore pressure started to decrease when the temperature started to stabilize. A higher excess pore pressure was registered in store No. 1 than in store No. 2 at 9 metres depth, due to a higher rate of heating.

In Figure 5, total settlements measured at the centre of each store can be studied with respect to temperature change. The settlement follows the development of pore pressure in the stores. In store No. 1, a heaving was initially registered. Later the store began to settle. It appears that settlements began when the temperature gradient was slightly reduced. In June, a sudden increase in settlement rate occurred when the energy supply was closed. Store No. 2 was heated at a slower rate and only a slight heaving was registered. Since then, the store has been settling. The settlement curve co-varied with the temperature, as did the pore pressure.

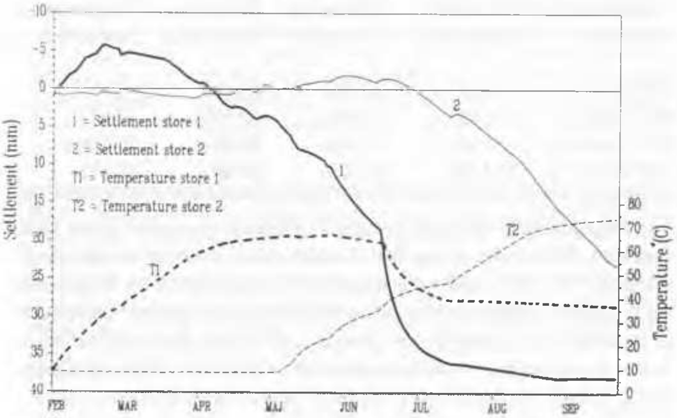

Figure 5. Development of settlement with temperature.

Shear strength was measured in situ in the stores to a depth of 15 metres with both field vane and dilatometer tests. The results are shown in Figure 8 and discussed in the part comparing field testing with triaxial testing.

TRIAXIAL TESTING

Triaxial testing at elevated temperatures required a special triaxial cell. A standard triaxial cell was equipped with heating elements, thermometers and a thermostat unit, see Figure 6. Three heating elements in the form of 50x100 mm foil were placed vertically around the specimen in the cell. One thermometer was used as a guide for the heat-servo controller. An other one was positioned close to the middle of the sample registered the temperature. It was possible to hold temperatures within ±0.1 °C. Careful calibration of temperature influence on each transducer were performed. Only slight differences in the pressure transducers were found, less than 1 kPa, when comparing readings for 20 and 70 °C under working stresses.

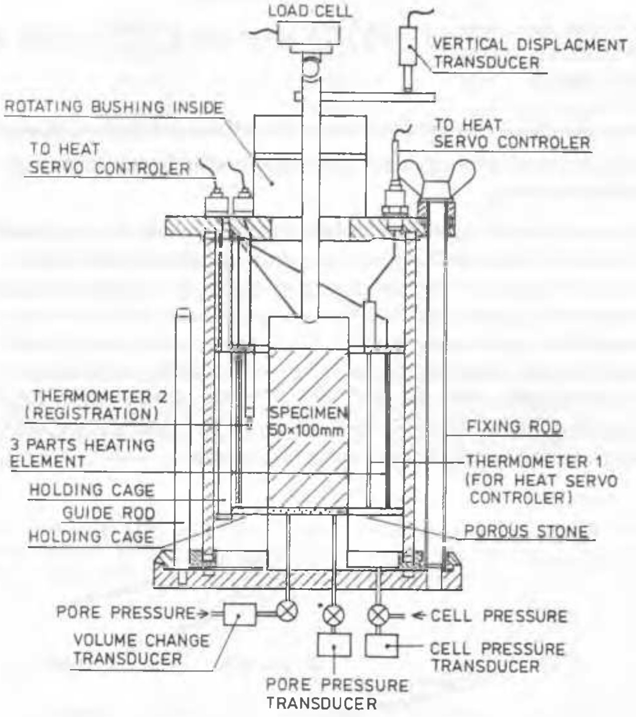

Figure 6. Specially equipped triaxial cell for testing at elevated temperatures.

Triaxial testing was performed on twelve undisturbed clay samples. Testing was defined so as to include samples from two depths and three different temperatures, and to shear them at two different strain rates. The specimens were consolidated to in situ stresses in three steps: isotropically and anisotropically in two stages.

After hydraulic consolidation (usually after three days) thermal consolidation followed in drained or undrained conditions. This enabled volume changes and pore pressure changes to be monitored. Three temperatures were chosen: 8, 40 and 70 °C. For 8 °C (corresponding to in situ temperature) no thermal consolidation was used, since specimens were stored and tested at that temperature. Shearing started immediately after hydraulic consolidation. Thermal consolidation (adaptation) at 40 and 70 °C took place after hydraulic consolidation at 20 °C.

Finally, undrained shearing was performed at vertical strain rates of 1 %/min (equivalent to quick undrained shearing) and at 0,006 %/min. The latter was planned in order to study development of effective stresses.

Results From Triaxial Testing

The results from the hydraulic consolidation showed volume changes up to 4 % until the insitu stress state was reached. This change applied to all the specimens except two, where the volumetric strain value was nearly doubled. These two were taken in the same bore hole and were probably disturbed during the sampling. They were both tested in 8 °C and taken from a depth of 9 metres.

While heating the samples under undrained conditions the pore pressure increased and the specimens swell. The expected pore pressure changes can be estimated by the equation (1):

Temperature and depth		Calculated value from equation (1)	Measured value from triax. test
40 °C and 6 m	Δu=	15.1 kPa	13 kPa
40 °C and 9 m	Δu=	9.5 kPa	15 kPa
70 °C and 6 m	Δu=	28.8 kPa	27 kPa
70 °C and 9 m	Δu=	37.3 kPa	35 kPa

The results obtained by equation (1) correspond well to the measured values from triaxial tests.

The results from the quick undrained shearing tests were slightly overrated, whereas the results from the slower tests were better adjusted to the soft clay. As a consequence of this, the discussion and results are based on the shearing tests of a rate of 0,006%/min. In Figure 7 some results from these shearing tests are presented. From the depth of 6 metres there is an obvious reduction of the shear strength peak values with increasing temperature. At 9 metres depth the shear strength does not follow that trend so obviously. Note that the results of the specimens tested at 8 °C not are significant, since they most likely were disturbed during the sampling.

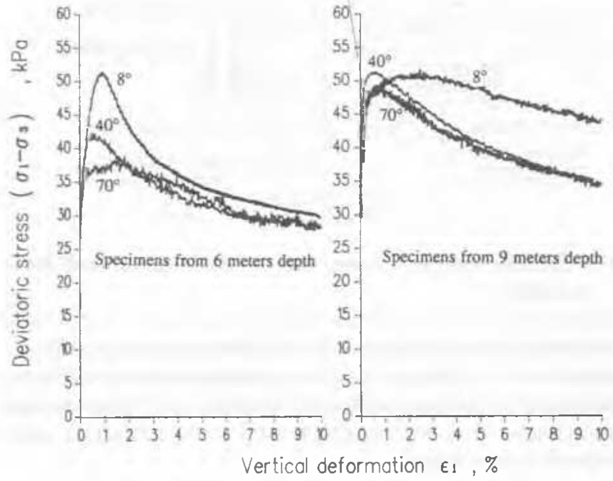

Figure 7. Results from shear tests with clay from 6 and 9 m depth.

COMPARISON OF RESULTS FROM THE FIELD AND THE TRIAXIAL TESTING

The results from field soundings of shear strength have been compared with the triaxial test results in relation to temperature changes and depth in Figure 8. The field soundings consist of measurements made by vane and dilatometer tests in store No. 2. Obviously the shear strength decreases with higher temperature. The values from the triaxial testing are as usual somewhat overrated. Still, the same decline as for the field soundings can be observed. The decrease in shear strength at 70 °C is about 30 % of the original values irrespective of test method.

Another interesting comparison between the field and the triaxial testings are the excess pore pressures. A comparison between calculated values from equation (1) and measured values from triaxial testing have already been done in the part about results from triaxial testing. When the maximum values from the measured excess pore pressures at the temperatures 40 and 70 °C from store No. 1 and No. 2 in Figure 4 the comparison will be complete.

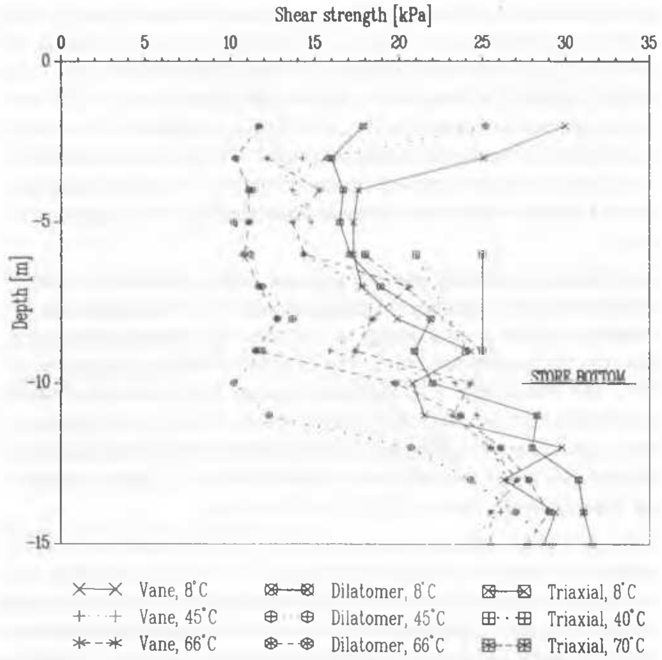

Figure 8. Shear strength of clay at different temperatures determined in situ and from triaxial testing.

Excess pore pressure, Δ_u				
Temperature and depth	**Calculated Equation (1)**	**Measured Triax.test**	**Measured Store No.1**	**Measured Store No.2**
40 °C and 6 m	15.1 kPa	13 kPa	16 kPa	12 kPa
40 °C and 9 m	19.5 kPa	15 kPa	50 kPa	28 kPa
70 °C and 6 m	28.8 kPa	27 kPa	20 kPa	25 kPa
70 °C and 9 m	37.3 kPa	35 kPa	62 kPa	40 kPa

The measured field values at the depth of 9 metres were much greater than expected. This is due to the fact that the water wants to expand in all directions but horizontally this expansion is counteracted by the passive earth pressure. This leads to an increase in passive earth pressure that results in an additional increase in pore pressure. The consequence of this fact is that in order to obtain realistic conditions in a laboratory when simulating a heat storage, the horizontal pressure, σ_3 has to be increased as well.

CONCLUSION

The investigations both in field and laboratory indicate the following changes in behaviour of soft clay due to heating:

- The pore water expands and the pore pressure increases if the drainage is limited.
- The expansion of pore water causes a swelling and an excess pore pressure, which start a consolidation process resulting in settlement.
- The maximum excess pore pressure can be estimated theoretically with adequate accuracy, noting that a high passive earth pressure causes an additional increase in excess pore pressure.
- The shear strength decreases about 30% at a temperature of 70 °C.

REFERENCES

Campanella, R. G, Mitchell, J. K. (1968). Influence of temperature variations on soil behaviour. ASCE, Vol 94, No SM3.1, pp 709-734.