Hydrodynamic and mechanical aspects of heat transfer in clay

Aspects hydrodynamiques et mécaniques de la diffusion de la chaleur dans les argiles

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SYNOPSIS The behaviour of natural soils subjected to temperature changes has been extensively studied in past decades particularly with reference to frost and geothermal problems. More recently, the potential use of geologic media as disposals for radioactive wastes has been considered, and thus there is a growing need for specific studies on the behaviour of soils and rocks in contact with heating elements. This paper deals with an experimental and theoretical work on this topic and in particular the variation of temperature, pore-water pressure and displacements produced by heating a clay mass under different boundary conditions. The experimental program was carried out in the laboratory on large blocks of overconsolidated undisturbed clay and on remoulded specimens of normally consolidated clay. Comparisons between the experimental data and the theoretical values obtained by the simple model of diffusion and by the coupled consolidation theory are presented and discussed.

INTRODUCTION

The study of the behaviour of natural soils and rocks subjected to thermal loading has become increasingly important in recent years as a consequence of the large use being made now of nuclear energy which however raises serious problems in relation to the disposal of radioactive wastes.

This problem has been tackled by many countries by selecting appropriate geological sites and studying their mechanical, thermal and hydraulic characteristics. An actual literature has been developed on this topic, but to date, a number of problems still await a solution. At the last Conference on Field Measurements in Geomechanics held in Zurich in 1983, W.Hustrulid, in his lecture on Design of Geomechanical experiments for Radioactive Waste Disposal, said: ".. *experiments to date have sometimes raised more questions than they have answered* " Thus the need for a greater insight into this problem seems urgent.

Within the European Community a common research program on radioactive waste disposal was developed (EEC,1981), each country studying a particular problem: Germany, evaporitic formations; France and England, granite rocks; Belgium and Italy, clayey formations.

This paper deals with some preliminary results of a research on heat transfer in clayey soils. Some selected results of laboratory tests are presented and discussed, attention being focused particularly on the heat diffusion process and on its hydrodynamic and mechanical effects.

EXPERIMENTAL PROGRAM

Two different series of tests - D-tests and C-tests - were used in the experiments. The D-tests were mainly conceived to verify the capability of the mathematical model of simple diffusion to predict the distribution of temperature increments produced in the sample by an electrical heater. These tests were carried out on samples obtained from large blocks from the Trisaia overconsolidated Plio-Pleistocene clay; only temperature changes within the sample were monitored during the tests.

With the C-tests a more complete set of measures were obtained from experiments. Remoulded samples from the Fiumicino Holocene clay were used in the tests; pore pressure changes and deformations related to the heating process were measured. The main geotechnical properties of the clays used in the experiments are reported in Table I.

For the D-tests, 49 cm diameter and 50 cm high cylindrical samples were trimmed from undisturbed blocks of the Trisaia clay. An electrical resistance, closed in a 1.7 cm diam. brass tube filled with silicon oil, was inserted in a hole drilled along the axis of the sample. Temperature measurements were made by J-type thermocouples driven into the sample at various depths and distances from the heater. Thermocouples were also installed in the heater and along the sides of the sample to control the boundary conditions for the diffusion process. In order to minimize the thermal gradients along the axis of the sample and therefore to simplify the interpretation of the experimental data, two discs, 5 cm thick, of polystyrene were placed at both ends.

The D-tests were all carried out in undrained conditions, with the surface coated with paraffin wax. The scheme of the experimental equipment used in such tests is represented in Fig.1.

Electrical powers of 20 and 30 watts were supplied to the heater; this corresponds to 0.75 and 1.12 kW/m^2 respectively. Maximum power was applied instantaneously and kept constant for about 40 hours. Then the power was suddenly removed but temperature readings were taken during the following 20 hours also.

In the C-tests, remoulded specimens of normally consolidated clay were used to obtain more reliable measurements of

Table I - Geotechnical characteristics of the tested clays.

	LL (%)	IP (%)	CF (%)	γ (kN/m^3)	W (%)	S_r	λ	k	K (m/s)	c' (kPa)	φ'
TRISAIA UNDISTURBED CLAY	53	32	45	27.4	26	0.98	0.200	0.020	$4\cdot10^{-11}$	4	23
FIUMICINO REMOULDED CLAY	68	43	42	27.5	59	1	0.243	0.043	$1.6\cdot10^{-10}$	0	25

the excess pore pressure induced by thermal loadings. Moreover, in order to establish well-controlled boundary conditions in terms of stresses and pore pressures, a 4-inch triaxial cell was used. The cell, suitably modified, allows for the insertion of micropiezometers and thermocouples from the pedestal into the sample. The piezometers consist of thin hypodermic needles connected to a strain gauge pressure transducer. All the specimens, 12 cm high, were trimmed from a large remoulded sample consolidated to 40 kPa in a Rowe-type oedometer. The scheme of the equipment is shown in Fig. 2.

The heater was obtained by placing an electric resistance into the loading head of the cell. A porous stone at the base of the specimen allowed drainage of the water; a thermocouple was installed into the heating head, while three other thermocouples were placed to monitor the temperature at the boundaries of the specimen and in the ambient ambient; the specimens were insulated by rubber membranes from the silicon oil, used as cell fluid.

Before the heating phase, each specimen was isotropically consolidated up to p' = 200 kPa. Full saturation of the clay was guaranteed by a back pressure of 300 kPa. After consolidation, an electrical power of 44 watts (5.6 kW/m²) was instantaneously applied and kept constant for four days. The power was then completely removed but the data recording was continued for two more days.

ANALYSIS OF THE EXPERIMENTAL RESULTS

A typical result of the D-tests is shown in Fig. 3a, where the temperature changes with time for W = 30 watts are reported. A maximum temperature increment of about 30°C was measured with this test. The curves show a sharp temperature change during the first hour of heating and values near the steady state condition after one day. Very similar changes but of opposite sign were observed during the cooling phase after the power break. The radial distribution

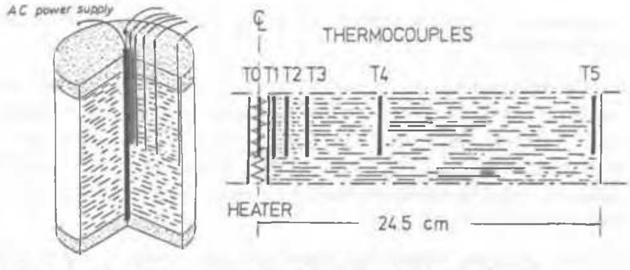

Fig.1 Experimental equipment used in the D-tests

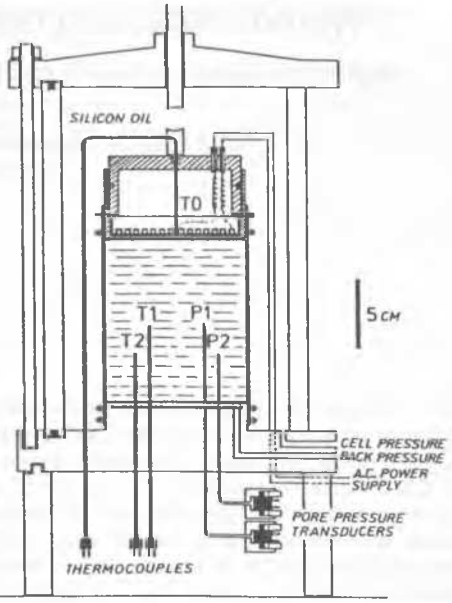

Fig.2 Modified 4-inch triaxial cell used in the C-tests

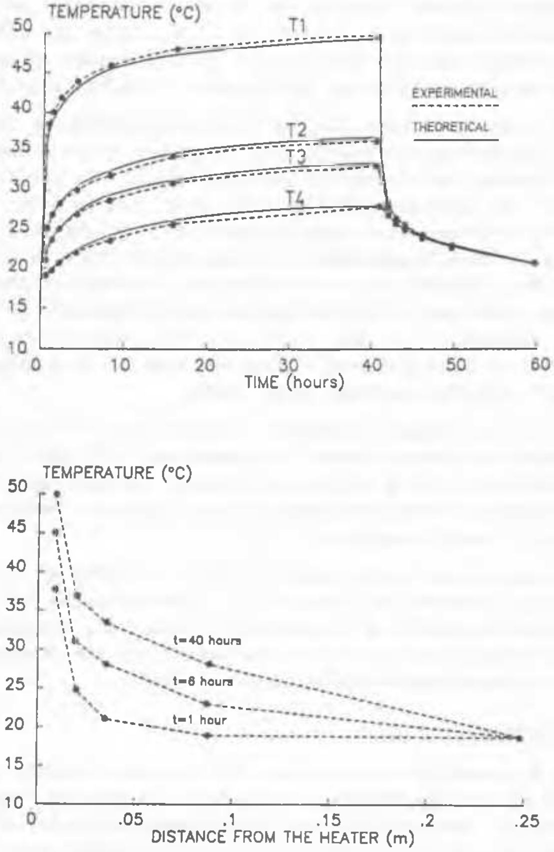

Fig.3 D - Test : Temperature changes with time (a) and their radial distribution (b)

of temperatures at different times during the test is reported in Fig. 3b.

Experimental data have been compared with the results obtained by the diffusion theory. By neglecting the effect of mass transport because of the low permeability of clays, the corresponding equation can be written, using polar coordinates, in the following form:

$$(\lambda T,_r),_r + (\lambda/r)T,_r + q - c\rho T,_t = 0 \qquad (1)$$

where
λ : thermal conductivity
c : specific heat
ρ : density
q : internal heat source

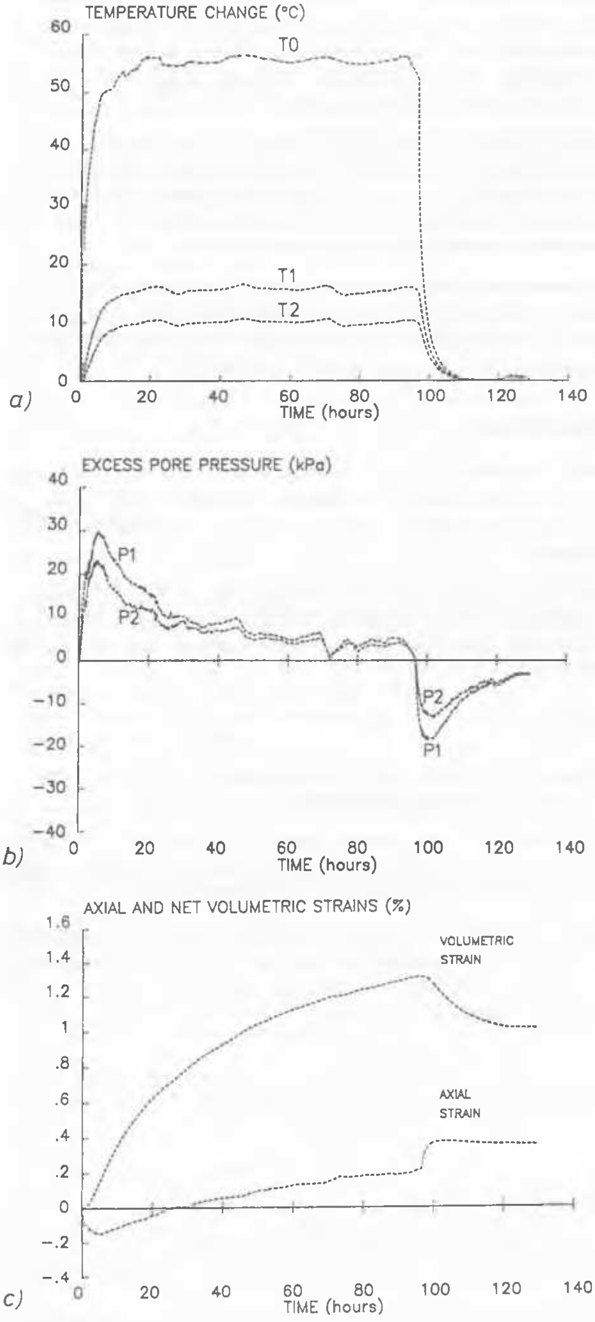

Fig.4 C - Test : Temperature (a), pore pressure (b) and strain (c) changes with time

Eq. (1) was solved numerically with the appropriate boundary conditions. By a fitting procedure the following values of the thermal characteristics of the Trisaia clay were found:

$$\lambda = 1.6 \frac{W}{m°K} \qquad c\rho = 2 \cdot 10^6 \frac{Ws}{m^3 °K}$$

Using the same values a good fit was obtained for the test where W = 20 watts; moreover, they agree with those measured on the same clay by other authors (GERA et al.,1976).

Experimental results of one of the C-tests are shown in Fig.4 where the temperature, pore pressure and strain changes with time are reported for a cycle of thermal loading and unloading.

Temperatures rose very quickly during the first six hours of heating and reached stationary values after about one day. Similar variations were observed during the cooling phase (Fig.4a). Maximum values of about 16°C and 10°C were measured by the thermocouples T1 and T2 respectively, whereas the corresponding temperature change at the heater was about 55°C.

As a consequence of the thermal water expansion, pore pressures increased rapidly in the early stage of the test and maximum changes of 30 and 23 kPa were measured after about six hours by the piezometers P1 and P2 (Fig.4b). Afterwards, the process of hydraulic diffusion prevailed over the thermal effects and dissipation of pore pressure was measured for four more days. A similar behaviour was observed during the cooling phase.

A closer inspection of the temperature and pore pressure curves, shows a correspondence between the change in temperature rate and the maximum pore pressure. This behaviour is probably to be related to a mass transport effect, although only to a small extent.

The diagrams in Figs.4c show the changes with time of the axial and net volumetric strains. The latter do not correspond to the actual volumetric changes of the specimen, as these depend also on thermal expansion. This term refers to the volume of water crossing the pervious boundary of the specimen and therefore it has been used to represent the consolidation effect.

The axial strain changes reflect the variations in pore pressure. After an expansion in the early stage of the test (where maximum expansion coincided with that of the excess pore pressure), a progressive reduction of the specimen height was found during the following days. A further, but sudden, axial reduction occurred after the power break and the final value ε_a = 0.4% was then reached.

Finally, regarding the consolidation effect of the thermal cycle, the maximum net volumetric strain ε_v = 1.3%, and a final value ε_v = 1.0% were measured.

In order to describe, in an analytical form, the hydrodynamic effects of the thermal loading on the clays and the corresponding deformations, a numerical model of coupled consolidation was used. This model is based on the modified Cam-clay constitutive law (BURLAND, 1965) and accounts for temperature effects through equivalent body forces.
The governing equations are:

$$C^{t}_{ijkl}(\dot{\varepsilon}_{kl} + \alpha\dot{T}) + \dot{u},_{j} = 0$$

$$(K_{ij}(u,_{j})),_{i} + \varepsilon_{v},_{t} - [n\alpha_{w} + (1-n)\alpha_{s}]\, T,_{t} = 0$$

where C^{t}_{ijkl} : stress-strain tensor

K_{ij} : permeability tensor

α : thermal expansivity of soil

α_{w} : thermal expansivity of water

α_{s} : thermal expansivity of skeletal material

n : soil porosity

These equations were solved by an F.E.M. technique, and the the results corresponding to the material properties in Table I and the boundary conditions of the present case, are reported in Fig.5.

Although the theoretical results do not exactly match the experimental data, the assumed mathematical model seems to be in excellent qualitative agreement with the observed behaviour.

FINAL REMARKS AND CONCLUSIONS

Although the experimental work is still in an early stage, preliminary conclusions may be drawn.

Heat transfer in clays may be represented, without serious errors, by the simple diffusion theory. This depends mainly on the low permeability of such soils, which therefore are not influenced by phenomena of mass transport. The field of temperature changes may be thus evaluated without keeping account of the fluid flow.

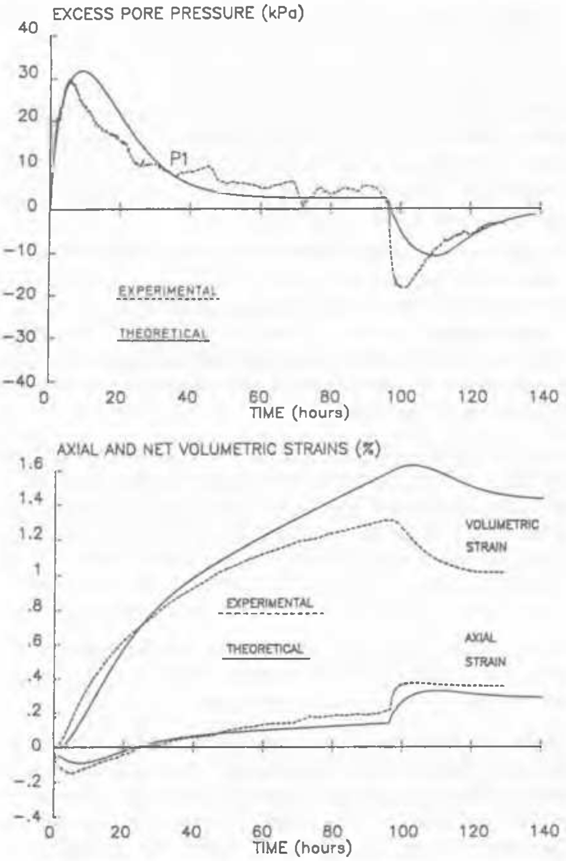

Fig.5 Comparison between theoretical and experimental results for a C-test

The mechanical effects of clay heating consist mainly in thermal and consolidation strains. Thermal strains depend on temperature changes, the bulk modulus of the solid skeleton and especially on the thermal expansivity of the fluid phase. Due to the latter effect, these strains are almost recovered when the heat supply is cut off. Consolidation strains depend on the constraint between the solid and liquid phase. Pore pressure rises during the early stage of the heating process until temperature changes develop. Later,when stationary thermal conditions are reached, the hydrodynamic effects prevail and the consolidation process takes place.

A first tentative analytical model of the observed behaviour was developed. The model is based on Cam-clay stress-strain relationships and allows for thermal effects through equivalent body forces. The corresponding equations were numerically solved by the F.E.M.

The comparison between experimental and analytical results shows a good qualitative agreement but further work on this subject is required so as to reach a better quantitative representation of experimental evidence.

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