Panel contribution: Suction and temperature, critical factors affecting soil behaviour

Contribution au débat: Succion et température, facteurs critiques du comportement des sols

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ABSTRACT: The need to tackle some novel geotechnical problems requires the incorporation of the effects of suction and temperature into current understanding of soil behaviour. The paper reviews recent advances in this field of research focusing in three main areas: laboratory testing, in situ testing and monitoring and physical modelling. Special attention is given to the development of a triaxial apparatus with simultaneous control of suction and temperature and to the in situ measurement of suction.

RESUME: La nécessité de répondre à de nouveaux problèmes géotechniques demande d'incorporer les effets de la succion et de la température dans les cadres actuels de compréhension du comportement des sols. L'article fait une révision des avances récentes dans ce domaine en se focalisant sur trois axes principaux: essais de laboratoire, essais in situ et contrôle et modélisation physique. Une attention spéciale est portée sur le développement de l'appareil triaxial avec contrôle simultané de la succion et de la température ainsi que sur la mesure in situ de la succion.

1 INTRODUCTION

The range of potential applications of Geotechnical Engineering is becoming increasingly wider. If novel problems are to be tackled with success, it is imperative to increase current understanding of soil behaviour and to extend existing conceptual frameworks in order to include new phenomena and their associated relevant variables. Two such variables are discussed in this paper: suction and temperature. Consideration of suction is essential for a proper understanding of the behaviour of unsaturated soils. Research carried out during the last decade has demonstrated conclusively that suction, the negative pore water pressure present in unsaturated soil, plays a central role in controlling their behaviour (Burland and Ridley, 1996; Fredlund and Rahardjo, 1993). In addition, the effects of temperature must be taken into account when dealing with non-isothermal situations.

The storage of high level radioactive waste in deep geological formations is an example of an engineering problem in which both suction and temperature are critical factors of behaviour. Most repository schemes envisage storing the canisters containing the waste in drifts or boreholes excavated in a suitable host rock. To ensure appropriate sealing of the waste, the canisters are surrounded by an engineered barrier made up of compacted swelling clay. The barrier is, at least initially, in an unsaturated state and is subjected to thermal loading from the heat given out by the waste. The thermal loading, the hydration of the unsaturated clay and the associated mechanical effects lead to a very complex coupled behaviour that must be well understood if the safety of the repository is to be assured.

Therefore, it is necessary to extend current understanding concerning saturated soils under isothermal conditions to include the effects of suction and temperature, as indicated in Figure 1. This generalisation can in fact be carried out using the same basic principles and methods used in conventional saturated Soil Mechanics (Alonso *et al.*, 1990; Gens, 1995a, 1995b; Hueckel and Borsetto, 1990). If present conceptual models can be represented by Figure 2a, their extension can be conveniently summarized by the addition of two additional axis, one representing suction (Fig, 2b) and one representing temperature (Fig. 2c). It can be noted that the effects are opposite, the surface associated with large scale yielding increases in size with suction because of the stiffening and strengthening effects of an increasingly negative pore pressure. In contrast, an increase in temperature weakens the soils and, accordingly, the large scale yield surface reduces. Information is still too scarce to suggest what form the internal yielding surfaces should have in the extended framework.

In this paper, recent significant developments in this research field are briefly highlighted. Naturally, because of space limitations, the paper does not attempt to be a state-of-the-art of the subject. The aim is simply to convey a flavour of recent advances and to identify areas where further research is required. Three main topics are addressed: i) laboratory testing, ii) in situ testing and monitoring and iii) physical models.

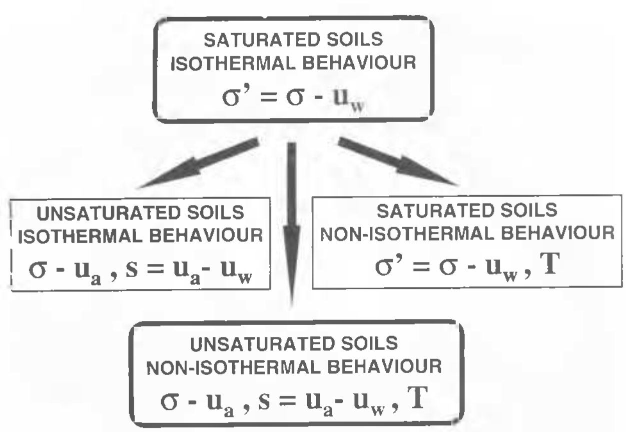

Figure 1. Incorporation of new variables and phenomena into current understanding of soil behaviour.

2 LABORATORY TESTING

Recent developments in this area have been reviewed in Juca and Frydman (1995). The following ones can be noted:

- development of new suction-controlled equipment (triaxial cell, oedometer with lateral stress measurement, direct shear apparatus, permeameters)
- improvement of osmotic technique for suction control
- introduction of new suction measuring techniques or devices (Imperial College tensiometer, psychrometer)
- development of testing equipment with simultaneous control of suction and temperature.

The equipment in which temperature and suction can be simultaneously and independently controlled are specially relevant to the subject of this paper. Two such apparatuses have been recently developed: an oedometer (Romero *et al.*, 1995) and a triaxial cell (Romero *et al.*, 1997). An scheme of the triaxial apparatus is shown in Figure 3. Matric suction is controlled by

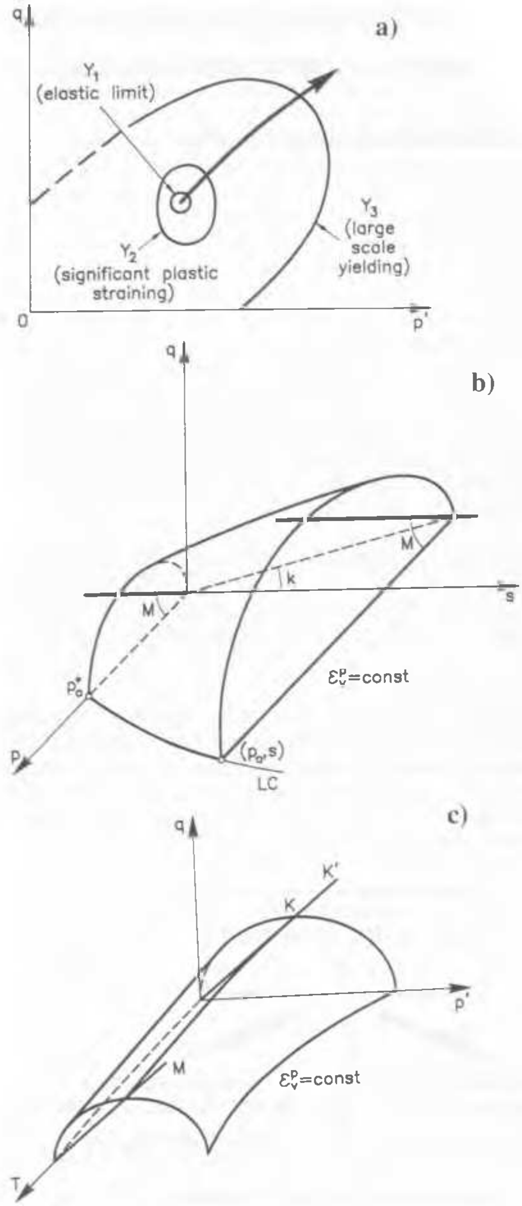

Figure 2. a) Yield surfaces for saturated soils (from Jardine, 1992) b) Large scale yield surface for unsaturated soils c) Large scale yield surface for non-isothermal conditions.

means of the axis translation technique in which an elevated air pressure is applied to the specimen. Positive water pressures can still be used while maintaining the required difference between air and water pressure, i.e. the prescribed matric suction value. Temperature is controlled by a forced convection circulation system of the cell fluid, silicon oil. The cell fluid temperature is achieved in an external heating chamber and is controlled by the readings of a thermocouple placed very close to the specimen.

The biggest challenge in an apparatus of this kind is the independent measurement of the volume changes of the specimen. Axial deformations are measured internally using two miniature LVDT transducers. The radial displacements are monitored by means of a non-contact electro-optical laser system mounted outside the chamber. Because the radial measuring system can slide vertically along the support rods, it is possible not only to measure the displacements of a fixed point on the specimen but to obtain the full vertical profile of the sample at any given time. Figure 4 shows the evolution of lateral profiles during a test in which the temperature is increased from 22°C to 50°C. As an example of the kind of results that can be obtained in this type of apparatus Figure 5 is presented. Two specimens of compacted Boom clay, one normally consolidated and the other overconsolidated were subjected to a thermal cycle. The tests were run at a constant controlled matric suction of 0.2MPa. The contrasting behaviour of the two specimens is readily apparent; whereas the overconsolidated specimen dilates upon heating, the normally consolidated sample compresses. Both samples contract during the cooling branch of the cycle.

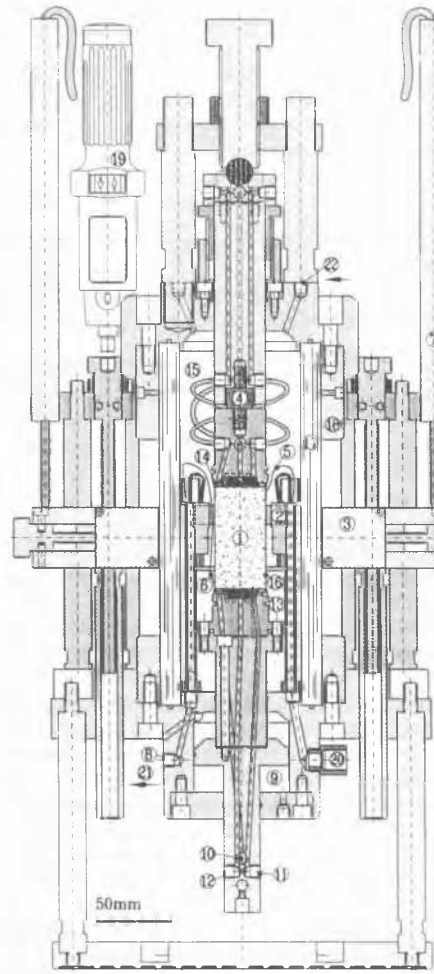

Figure 3. Layout of the triaxial cell with control of suction and temperature (Romero *et al.*, 1997).

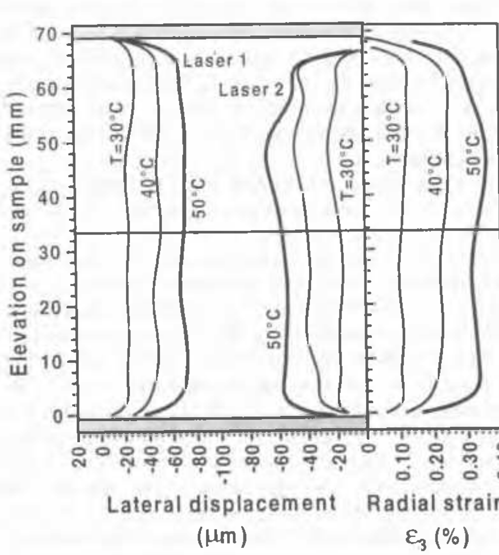

Figure 4. Lateral profiles of an specimen subjected to an increase of temperature (Romero *et al.*, 1997).

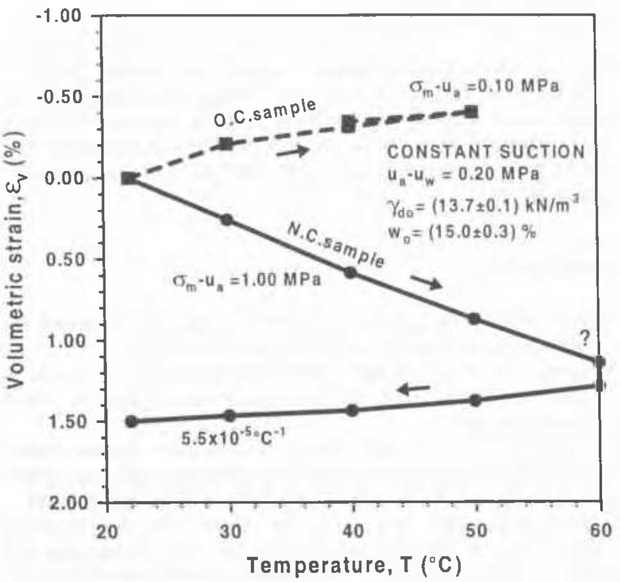

Figure 5. Volumetric strains observed in non-isothermal tests at constant suction on compacted Boom clay (Romero, 1997).

3 IN SITU TESTING AND MONITORING

Perhaps it is in the area of in situ testing and monitoring that the pace of recent development is fastest. Some recent noteworthy advances are:

- Development of plate loading tests for unsaturated soils (Conciani, 1997; Ferreira and Lacerda, 1995; Houston *et al.*, 1995)
- Pressuremeter tests for unsaturated soils (Ridley *et al.*, 1997)
- Long term monitoring of field test sites (Delaney *et al.*, 1996, Fredlund *et al.*, 1995; Jucá *et al.*, 1995).
- In situ measurement of suction.

The last item, the in situ measurement of suction, is a most fundamental development. Because of the central role that this variable plays in unsaturated Soil Mechanics, reliable measurement of suction in the field is a necessary requirement for further advances. All the devices listed in Table 1 have been used for the in situ measurement of suction in recent times. It can be observed that they have different ranges, capabilities and equilibrium times, so there is not a single method valid for all situations. In fact the TDR device measures water content and not suction, but it has been included in the list because it is an interesting and potentially useful innovation. Perhaps one of the most significant advances is the Imperial College suction probe (Ridley and Burland, 1993) that is able, for the first time, to measure directly absolute negative pore pressures. It has been now used successfully in a number of field applications (Ridley *et al.*, 1997). Other three suction measuring methods: capacitive probe, psychrometers and TDR will be discussed in connection with the description of a large scale physical model in the next Section.

Table 1. Methods used for in situ suction measurements

Device	Suction type measured	Range (MPa)	Equilibrium time
Filter paper	Total	0.4 - 30	7 - 14 days
Thermal conduct. probe	Matric	0 - 0.4	Weeks
Standard tensiometer	Matric	0 - 0.08	Minutes
Imperial Coll. tensiometer	Matric	0 - 1.8	Minutes
Psychrometer	Total	0.1 - 7.5	Minutes
Capacitive probe	Total	1 - 300	Minutes
T.D.R.	Water content	-	Minutes

4 PHYSICAL MODELS

As mentioned before, the behaviour of an engineered barrier around a radioactive waste canister involves the interaction of thermal, hydraulic and mechanical phenomena leading to a quite complex behaviour. Although partial approaches may be useful, the only way to observe the real behaviour is by means of a physical model. A full scale test is being carried out at present in the Grimsel Underground Laboratory in the Swiss Alps (Fig. 6). Two heaters, simulating the heat power of radioactive waste, are placed in the centre of a specially excavated tunnel. They are surrounded by compacted swelling clay and the whole experiment is sealed by a concrete plug. The test will be left in place for at least three years to check the effects of heating and hydration from the surrounding rock on the barrier.

The test is of course heavily instrumented. Here, only suction measurements will be referred to. Because different apparatuses have different capabilities, sometimes several have been placed together to cover the full range of expected measurements. Groups of instruments are then placed at different distances from the centre. The readings of the capacitive probes, psychrometers and TDR devices during the first months of the experiment are shown in Figures 7, 8 and 9.

Figure 7 shows the measurements of the capacitive probes in a typical instrumented section. Close to the rock, the clay shows significant hydration. In the centre of the buffer, we have a characteristic evolution that includes a peak. It is due to the effects of vapour diffusion. Finally, drying of the clay is measured close to the heater.

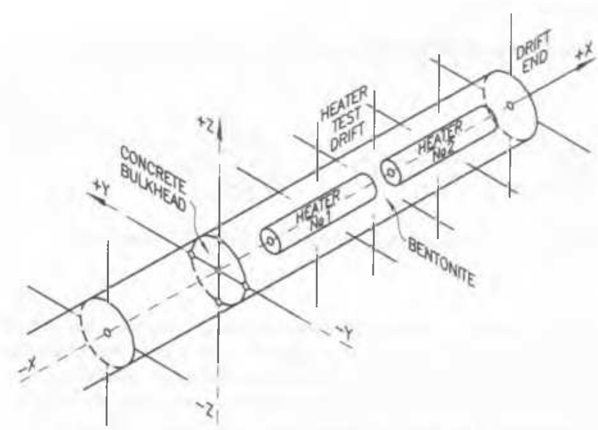

Figure 6. Scheme of the large scale in situ heating test.

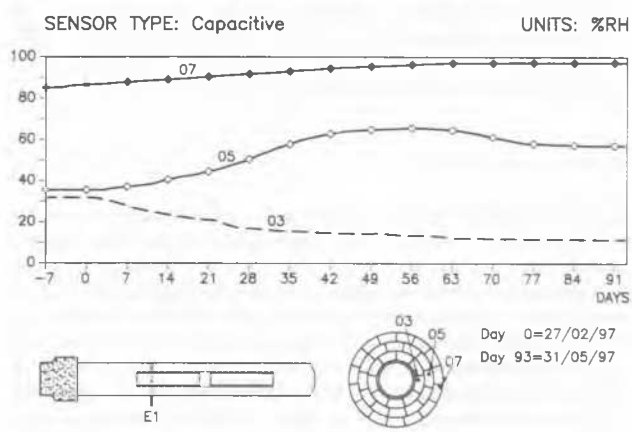

Figure 7. Relative humidity (total suction) measurements of the capacitive transducers.

In this range of suction the psychrometers provide less information (Fig. 8). However, the devices close to the rock/clay interface clearly show the progress of hydration. The same phenomena can be observed from the TDR measurements (Fig. 9). It can be stated, therefore, that in situ measurement of suction is

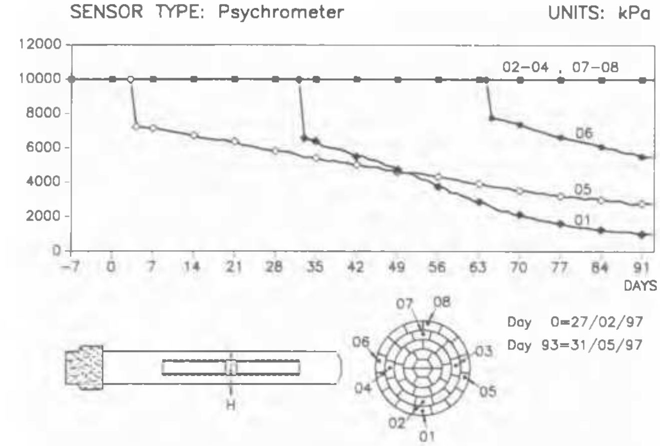

Figure 8. Total suction measurements of the psychrometers.

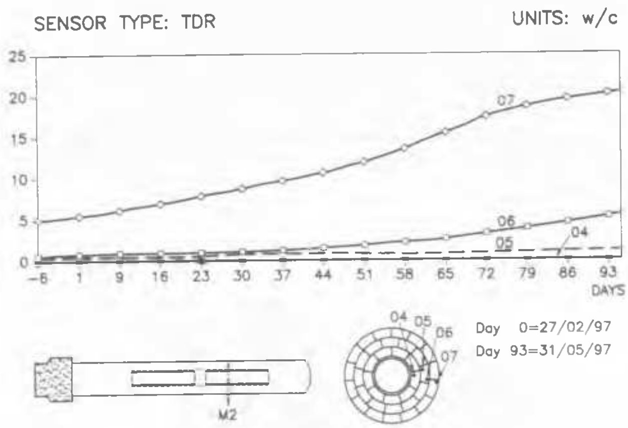

Figure 9. Water content measurements of the TDR devices.

certainly a viable proposition even in non-isothermal conditions. However much progress is still required in this area. Although the various advances reported are very encouraging, reliable in situ measurement of suction is still far from being achieved routinely.

Naturally the proper interpretation of the results of a physical model requires the performance of appropriate numerical modelling. In this case, it implies the performance of coupled thermo-hydro-mechanical analyses solving, simultaneously, the equation of equilibrium, water continuity and heat transport using adequate constitutive laws. The topic is outside the scope of this paper but details are given in Gens *et al.* (1998).

5 CONCLUSIONS

New problems and novel geotechnical applications require the incorporation of suction and temperature effects into current understanding of soil behaviour. This enhanced understanding can be integrated in a natural manner in theoretical frameworks that are extensions of models commonly used in saturated Soil Mechanics.

In this paper, recent advances in this area of research have been summarily reviewed. It must be said, however, that in spite of significant developments reported, further advances in laboratory and in situ techniques are required. Suction control, suction measurements in the field and in situ testing should be regarded as priority areas for research.

Finally, recent experience indicates that physical models provide an effective approach for the study of complex problems. Their correct interpretation, however, may require coupled thermo-hydro-mechanical numerical modelling if the problem involves unsaturated soil under non-isothermal conditions.

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