Temperature-controlled oedometer testing on compacted bentonite

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ABSTRACT:
A new temperature-controlled oedometer has been designed at Imperial College London and commissioned to investigate the thermo-hydro-mechanical behaviour of soils. Temperature control is achieved by submerging the specimen in a water bath. The water temperature is regulated by heaters positioned radially around the specimen, or by an external unit. The temperature can be varied between 5°C and 85°C. The temperature gradient across the specimen is minimised by circulating water beneath the specimen through a hollow plate. A thermo-mechanical, elastic, finite element model of the equipment has been produced using the Imperial College Finite Element Program (ICFEP). The experimental results are used to develop and validate the numerical model. The model is then used to inform and improve the experimental testing programme. The accuracy of temperature control has already been established. The testing programme includes heating tests at constant applied stress, and loading tests at discrete temperature values. Of particular interest is thermally-induced overconsolidation behaviour. The experimental results are used to verify the existing numerical framework and to establish the effect of temperature on the behaviour of saturated soil.

1 INTRODUCTION

A temperature-controlled oedometer has been developed at Imperial College London to provide high-quality data relating to the thermo-hydro-mechanical behaviour of soils.

This paper is organised as follows: there is a literature review of research relating to the thermal behaviour of soils and temperature-controlled oedometers; the limitations of these schemes and the case for further research is proposed; the design and development of the new oedometer is described; the development of the numerical model is discussed; the proposed test programme is introduced, followed by some concluding remarks.

Thermal testing of soils is relevant to geotechnical scenarios involving elevated or varying temperatures. It has direct application to the design of repositories for the deep geological disposal of nuclear waste and ground source heating/cooling systems. There is currently a shortage of information on the effects of temperature on soil behaviour. The unprecedented design life of nuclear waste repositories, in the order of 100,000 years, reinforces the need for data that will enable accurate predictions of long-term soil behaviour. Laboratory data, obtained over a (relatively) short time period, can be used to develop and validate numerical models, which can then simulate the full design life of a repository. Only through a combination of laboratory testing and numerical analysis can the questions relating to repository safety be satisfactorily answered.

Compacted MX-80 bentonite is used in the laboratory tests, due to its proposed use as a buffer material in deep geological disposal.

2 LITERATURE REVIEW

2.1 Thermal testing

The first scheme to investigate the thermal behaviour of saturated soil was Mitchell and Campanella (1964), which used a modified triaxial apparatus. Since then, triaxial apparatuses, oedometers, and large-scale in-situ tests in deep underground laboratories have been used to obtain data on thermal behaviour. Thermal testing using triaxial apparatus is covered in Martínez Calonge (2013).

An early oedometer scheme, Towhata et al. (1993), used a standard oedometer, modified to enable temperature to be regulated. All tests were carried out using saturated soil.

A more recent improvement in experimental capability is the development of oedometers that can control both temperature and suction, and can therefore test unsaturated soil behaviour. These oedometers can more accurately model the conditions in a repository, where there will be competing effects of heating and hydration. Two such oedometers were developed by Romero et al. (2005) and Francois and Laloui (2010). In both schemes, suction is controlled using the axis-translation technique. The upper limit for degree of saturation using this technique is 80%, and the maximum suction is 1.5 MPa (Standing, 2015).

These limitations can be overcome by using the relative-humidity (RH) control technique, in which suctions up to 300 MPa can be applied (Mantikos et al., 2016). The suction-controlled oedometer at Imperial College London uses the RH control technique. The eventual aim is to combine the suction-controlled oedometer with the temperature-controlled oedometer described in this paper, so that thermal behaviour of unsaturated soils can be investigated.

2.2 Thermal effects on saturated soils

Previous research such as Towhata et al. (1993) shows that over-consolidation ratio (OCR) has an important effect on the way saturated soil behaves when heated and cooled. Soils that are normally consolidated (NC) or overconsolidated (OC) behave differently, even in an opposite sense when considering volume change, e.g. contraction rather than expansion.

So far, there is not a consensus on the cause of this behaviour. Heating has a number of physical effects, which leads to a complex response. It is well understood that heating causes expansion of the pore water and the soil skeleton. It is also known that the pore water has a much greater thermal expansion coefficient than the soil skeleton. However, this alone cannot explain the contractive behaviour which is observed upon heating in NC and lightly OC specimens. In Towhata et al. (1993), it is proposed that increasing temperature reduces the thickness of the adsorbed water layer surrounding clay particles, allowing the particles to move closer together, leading to contraction.

This research aims to answer the following questions relating to saturated soil behaviour:

(1) Why do heavily OC specimens expand when heated, whereas lightly OC and NC specimens contract?

(2) Why do lightly OC specimen initially expand when heated, then contract?

(3) Why does contraction appear to be irreversible, but expansion reversible?

Even though there may not be an agreed physical explanation for the thermal behaviour, experimental data can still be used to inform numerical models. The idea of a thermal yield surface is used by Abuel-Naga et al. (2007) to explain the effects of OCR and temperature at loading.

3 DEVELOPMENT OF APPARATUS

3.1 Design

A schematic of the new equipment is shown in Figure 1. A photograph is shown in Figure 2.

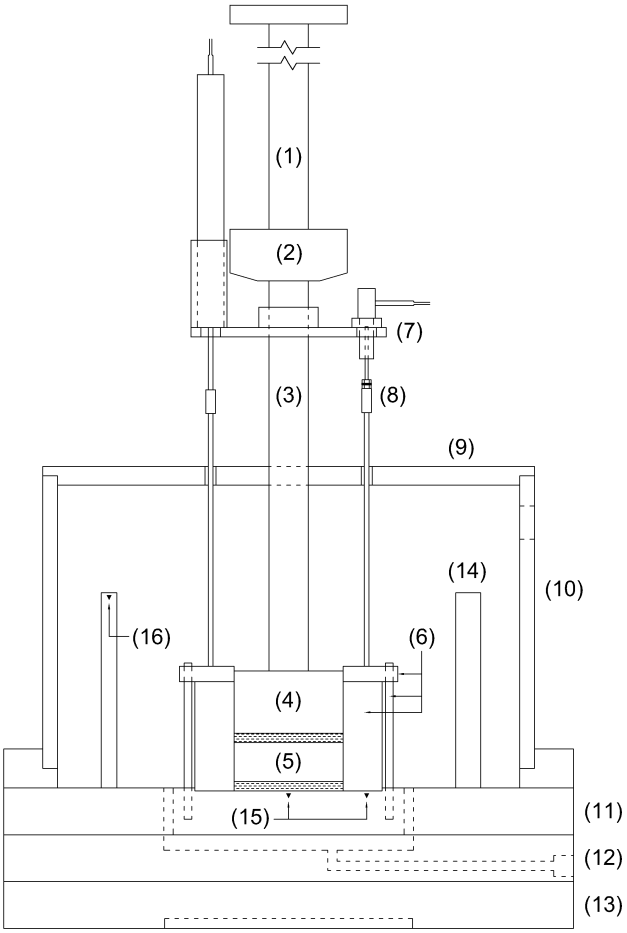


Figure 1. Schematic of the temperature-controlled oedometer at Imperial College London

(1) Loading ram (upper section)
(2) Load cell (up to 70kN)
(3) Loading ram (lower section)
(4) Top cap
(5) Soil specimen, between porous stones
(6) Confining ring
(7) Instrumentation plate
(8) Extension pieces for displacement gauges
(9) PVC lid
(10) PVC water bath
(11) Upper steel plate
(12) Lower (hollow) steel plate
(13) PVC base
(14) Brass heater
(15) Temperature gauges in upper plate
(16) Temperature gauge in water bath

The equipment is an original design that has been manufactured specifically for this purpose. With reference to Figure 1, components (1) to (6) are similar to a standard electronic oedometer. Vertical force is applied via a computer-controlled load frame which is shown in Figure 2.

Vertical displacement is measured using four displacement gauges. To minimise temperature effects on instrumentation, the gauges are positioned outside the water bath, on a plate (7), and connected to the confining ring via stainless-steel extension pieces (8). The PVC lid (9) and base (13) prevent excessive heat loss, as well as insulating the instrumentation above the water bath.

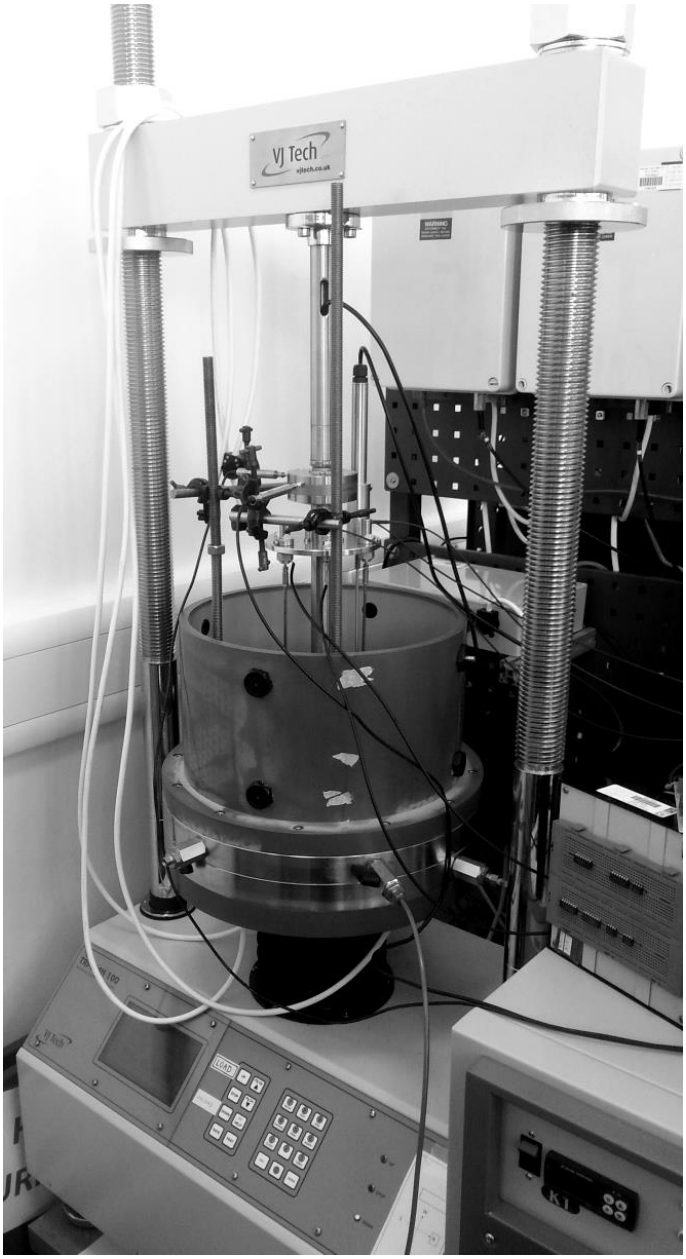


Figure 2. Photograph of the temperature-controlled oedometer at Imperial College London

The water bath is formed from a PVC cylinder (10), which sits above two stainless-steel plates (11) and (12). A novel feature of this oedometer is the lower plate (12), which has a hollow section directly below the specimen. Water drains down from the water bath, through the upper plate (11), and then spreads out in the hollow section of the lower plate. The water is then pumped out of the lower plate, and back into the water bath. Circulating water below the specimen heats it isotropically, which minimises the temperature gradient across the specimen.

Temperature is controlled using the water bath surrounding the specimen. The water is heated by up to twelve 150W electric heaters (14) within the bath. Using this system, temperature can be controlled between ambient (~20°C) and 85°C. Heating can also be applied using an external heating/cooling unit, which then circulates water through the water bath and lower plate. Using this system, temperature can be controlled between 5°C and 85°C.

Temperature is measured at three points - two beneath the specimen and confining ring (15) and one within the water bath (16). The measuring instrumentation and the heaters are connected to Triax, software that can be used to control variables such as temperature, force and displacement.

In a heating test with no soil specimen in position, the temperature was measured at locations (15) and (16). The difference between the measured temperature values increases with target temperature, as shown in Figure 3. A large temperature difference results in a steeper temperature gradient across the specimen. The temperature difference is much lower when the circulator is on. This suggests the unique circulation design of this oedometer is an improvement on previous designs.

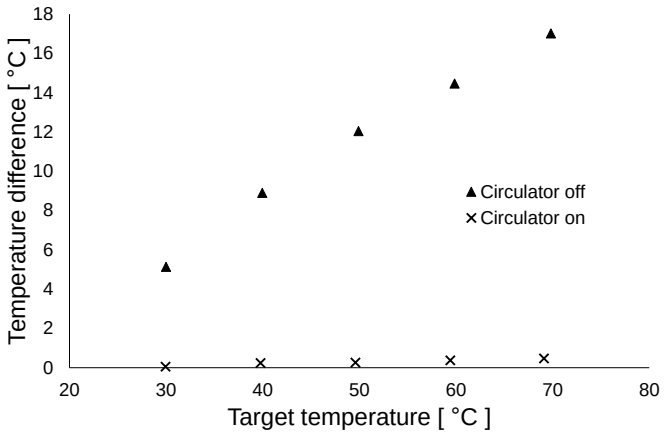


Figure 3. Difference in measured temperature at locations (15) and (16) for circulator on/off

3.2 Calibration

The following instrumentation in the TC oedometer requires calibration:
(1) The four vertical displacement gauges
(2) The load cell
(3) The three temperature sensors

One of the main difficulties with temperature-controlled apparatus is calibration. For example, calibration of the load cell, used to measure or control the applied load. The challenge is to determine whether the value measured by the load

cell is due to the swelling of the soil, swelling of the oedometer equipment, or a direct effect of temperature on the measuring instrumentation.

By moving the instrumentation outside the water bath and insulating it from the heat, excessive temperatures are avoided. However, the instrumentation still needs to be calibrated for the full range of proposed water bath temperatures.

4 NUMERICAL ANALYSIS

4.1 Introduction

A numerical analysis was performed using the Imperial College Finite Element Program (ICFEP) (Potts and Zdravković, 1999, 2001). The laboratory equipment was modelled in ICFEP and an axisymmetric, thermo-mechanical finite-element (FE) analysis was performed. The analysis used 3172 isoparametric, 8-noded, quadrilateral elements.

There are advantages to having both a physical and numerical model. The numerical analysis is not intended to replace laboratory testing, but can perform a range of complimentary functions.

4.2 Boundary conditions

4.2.1 General

So far, two analyses have been carried out, and further analyses are planned. Each analysis uses different boundary conditions. In both analyses, the boundary conditions for the mesh are as follows:

(1) *Prescribed displacements* – the vertical displacements along the base, and the horizontal displacements along the axis of symmetry, are fixed at zero.

(2) *Natural heat loss* – the ambient temperature value is fixed. This value is used in Newton's law of cooling to determine the temperature flux across the complete mesh boundary, except the axis of symmetry.

In addition to (1) and (2), for each analysis, another boundary condition, either (3) or (4), is prescribed:

(3) *Induced temperature* – the temperature of the heater is prescribed

(4) *Exchange heat flux* – the power output of the heater is prescribed

4.2.2 Comparison with laboratory data

The FE results were compared with the laboratory data. Figure 4a shows the mesh, and Figure 4b shows the location of two nodes, 1 and 2, and the comparable measured values, T_{bath} and $T_{specimen}$. Node 1 is close to the heater surface; Node 2 is beneath the surface of the upper steel plate. The test was a stepped heating/cooling cycle, with no soil specimen present and no water circulation.

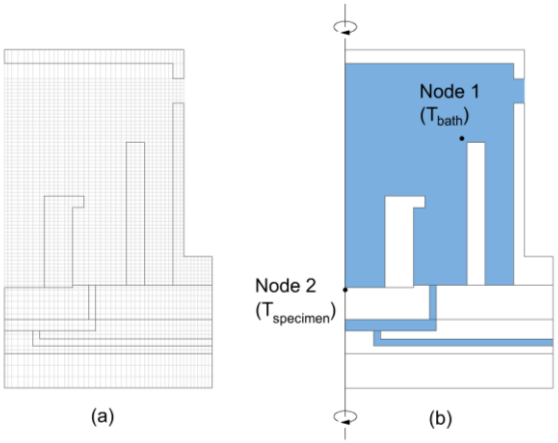


Figure 4. (a) Finite element mesh (b) Nodes (1 and 2) used for comparison with measured data (T_{bath} and $T_{specimen}$)

4.2.3 Induced temperature boundary condition

The temperature of the heater is prescribed. This drives the heating and cooling of the rest of the FE mesh. The input data, shown in Figure 5, is the temperature measured within the water bath, which is simplified into straight lines, of constant temperature, or constant rate of change. The data is input into the FE model by specifying the temperature of the heater elements within the mesh.

The FE results are shown in Figure 6. As Node 1 is located close to the heater, but not directly touching, the temperature is not the same as T_{bath}.

The induced temperature boundary condition implies that the heaters cool down the surrounding water. In reality, there are ongoing heat losses from the system to the surrounding air. The heaters are turned off until these heat losses bring the system to the target temperature. At this point, the heaters turn on (and off) to regulate the temperature at this level. It was this result that led to the adoption of the exchange heat flux (power) boundary condition, with the aim of simulating realistic cooling behaviour.

4.2.4 Exchange heat flux boundary condition

The power input from the heaters is prescribed, i.e. energy per second. It is then assumed that this energy is delivered evenly throughout the heater at a certain power per m^3 [W/m^3]. In an axisymmetric analysis it is assumed that energy is being delivered all around the specimen, from a heater shaped like a hollow cylinder, when actually it is coming from discrete points. This assumption is made in both analyses.

Although the input data for this boundary condition, shown in Figure 7, is more representative of real conditions, the FE analysis does not reproduce the measured results well, as shown in Figure 8. Neither boundary condition is able to simulate the large temperature gradient (difference between T_{bath} and $T_{specimen}$) which is observed when the water in the bath is not circulated. This may be due to not including buoyancy effects, which cause convection currents to form in the water.

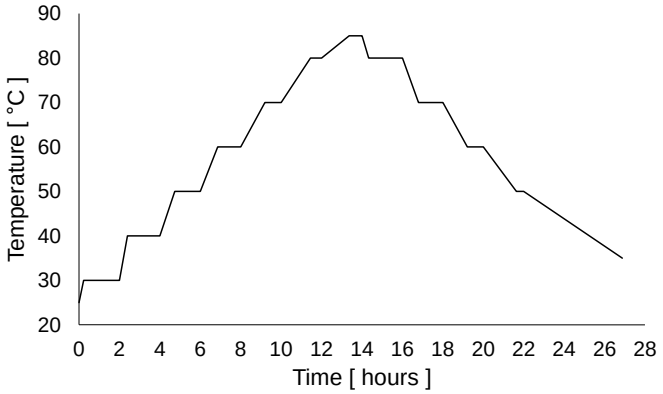


Figure 5. Induced temperature boundary condition – input for finite element analysis

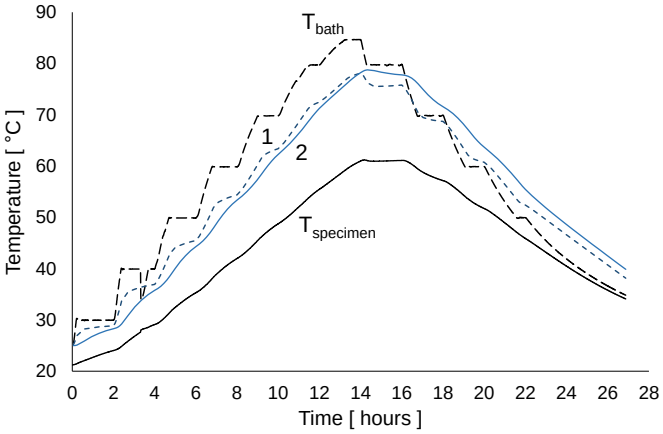


Figure 6. Induced temperature boundary condition – comparison between measured data and FE analysis

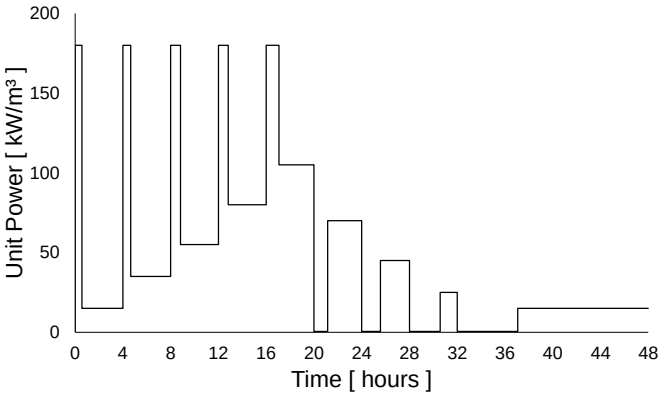


Figure 7. Exchange heat flux boundary condition – input for finite element analysis

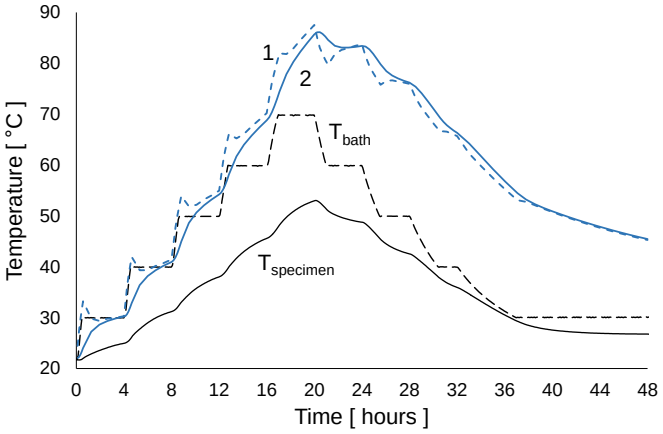


Figure 8. Exchange heat flux boundary condition – comparison between measured data and FE analysis

4.3 Parametric study

A parametric study was performed to determine the relative importance of the various thermal properties of water. The thermal parameters considered were:
(1) Specific heat capacity (c)
(2) Thermal conductivity (k, λ, or κ)
(3) Linear thermal expansion coefficient (α_L)

For each parameter, analyses were carried out in ICFEP, using the exchange heat flux boundary condition, introduced in the previous section.

Within the realistic range of values, only the linear thermal expansion coefficient had a potentially significant effect on temperature in the water bath. Based on this result, it may be useful to vary this value to the extremes of the realistic range in future analyses, and check that the final result is not affected significantly by this parameter.

4.4 Further analyses

4.4.1 Thermo-hydro-mechanical analysis

The analyses carried out so far have been thermo-mechanical analyses. Water was modelled in the analyses, but only its thermo-mechanical properties. Flow of water, or buoyancy effects, were not modelled. This is a limitation when trying to realistically model the actual behaviour of the water.

To overcome this limitation, the next step will be to model the flow of water. The analysis will therefore be thermo-*hydro*-mechanical. There are issues involved with modelling water flow, such as temperature fluctuations resulting from high Péclet number (Cui et al., 2016), which need to be resolved.

4.4.2 Three-dimensional analysis

It is also proposed to develop a 3D model of the equipment. This will be more computationally intensive to analyse. However, it has clear advantages over the axisymmetric analysis in terms of accuracy. The small scale of the problem means that the analysis should still be fast to run, and within the available computational capacity.

5 TEST PROGRAMME

5.1 Ambient temperature testing

Since data on the mechanical behaviour of MX-80 bentonite is limited, a programme of laboratory tests at ambient temperature (~20°C) is proposed. This data will be used to inform and improve the existing numerical models which incorporate soil properties. The tests will comprise characterisation tests (specific gravity, plastic and liquid limits); standard oedometer tests; triaxial tests (including creep effects).

The data from these tests will be compared with that obtained using the new oedometer, before continuing with the programme of temperature-controlled oedometer testing.

5.2 Temperature-controlled testing

Specimens will be loaded and unloaded to different overconsolidation ratios, then subjected to heating and cooling cycles.

Specimens will also be loaded and unloaded to the same overconsolidation ratios, then consolidated at different temperatures, to see what evidence of thermal yield can be observed.

5.3 Combined temperature and suction control

Looking further ahead, the aim is to combine this equipment with the existing relative-humidity controlled (suction-controlled) oedometer at Imperial College London, and thus investigate thermal effects on unsaturated soil.

6 CONCLUSIONS

A new temperature-controlled oedometer has been designed and developed at Imperial College London. Temperature can be regulated between 5°C and 85°C. A novel feature of the equipment is a hollow steel plate, which enables circulation of heated water beneath the specimen. This minimises temperature gradients across the specimen and ensures isotropic heating conditions.

Temperature control has already been established up to 85°C. Calibration of the measuring equipment at ambient temperature is complete. Calibration over the full temperature range is ongoing.

A testing programme has been developed, which includes heating tests at constant applied stress, and loading tests at discrete temperature values.

Alongside the thermal tests, there will be a series of tests at ambient temperature. The soil tested will be MX-80 bentonite.

An axisymmetric, thermo-mechanical, elastic, finite element model has been developed using the Imperial College Finite Element Program (ICFEP). Two different boundary conditions have been analysed, one using temperature data as input, and one using power data as input. The model will be further developed into a thermo-hydro-mechanical model by incorporating water flow. A 3D analysis is also planned.

The laboratory data will enable development of numerical models which simulate temperature change scenarios. The engineering applications include the design of repositories for the deep geological disposal of nuclear waste, and ground source heating/cooling systems.

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