PHYSICAL MODELLING OF CONTAMINANT TRANSPORT PROCESSES

P.J. HENSLEY* and C. SAVVIDOU+

1. INTRODUCTION

The objective of any modelling exercise is one of simulation and prediction. In the particular case of subsurface contaminant transport, modelling provides valuable information about the spread and growth of pollutant plumes, and the effectiveness of various containment and remedial action strategies. Modelling can thus offer much assistance in identifying the optimum course for environmentally sound waste management.

Various types of models are available. These include physical models, where a scaled model is tested in the laboratory or field; analogue models, where the process under examination is replaced by a process that behaves in a similar manner; and mathematical models, where the process is reduced to a set of governing equations, which are subsequently solved using either analytical or numerical methods.

This paper describes a physical modelling technique, namely centrifuge modelling, that has the potential to provide worthwhile assistance in the investigation of many contaminant transport processes.

1.1 Background

Prediction of the movement and accumulation of contaminants in groundwater flow systems is often carried out with the aid of theoretical models, that provide mathematical simulations of the problem under consideration. The results of any modelling exercise are wholly dependent upon both complete understanding of the fundamental processes involved, and accurate conceptual modelling of all relevant mechanisms.

In recent years, it has become apparent that a critical need exists for physical observations of pollutant behaviour in soils. Such observations are required both to validate existing mathematical transport models, and to aid us in developing improved conceptual models of fundamental transport processes.

Historically, controlled field experiments and laboratory column tests have provided the bulk of experimental data on pollutant behaviour in soils. Controlled field experiments have the advantage of modelling the total complexity of the full scale problem. However, these tests are costly, extremely difficult to perform and usually offer little direct control over boundary conditions. On the other hand, laboratory column experiments, which are generally inexpensive and relatively uncomplicated to perform, are often of limited value, due to their inability to model realistic boundary conditions.

Recently, researchers have come to recognise that a geotechnical centrifuge can provide a powerful experimental tool for investigation of many environmental engineering problems (Savvidou, 1988, Hensley and Schofield, 1991). A geotechnical centrifuge has the ability to model complex two and three dimensional problems, under repeatable and controlled boundary conditions.

The research presented in this paper investigated two environmental engineering problems, using the technique offered by geotechnical centrifuge modelling. The first problem concerned contaminant transport from a land based waste disposal site, and results from this investigation are compared with predictions from a theoretical transport code. The second problem concerned combined heat and contaminant transport from a buried waste source.

2. PRINCIPLE OF CENTRIFUGE MODELLING

The mechanical behaviour of a prototype soil mass under the earth's gravity g, can be replicated in a small scale model of $1/n$ experiencing a centrifugal force of ng, figure 1. If the product of depth times acceleration is the same in model and prototype, the stress distribution throughout the model will be identical with that throughout the prototype.

Centrifuge model tests therefore offer a means of carrying out small scale physical modelling of geotechnical problems, at stress levels similar to those experienced by the prototype.

Centrifuge modelling of environmental engineering problems is essential if stress gradients within the soil and/or gravitational forces influence the problem under investigation. Examples of problems where these factors may be important are given below.

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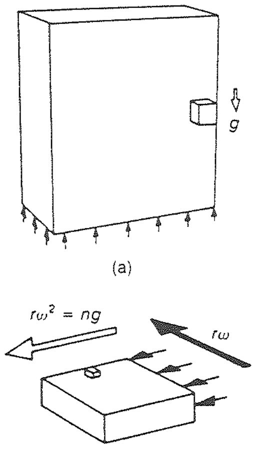
1) The movement of liquid pollutants in water bearing strata is heavily dependent upon soil permeability. The permeability of many compressible soils is a function of both the stress level and the stress history of the soil.

2) Physical transport due to gravitational forces will enter all waste transport problems involving convective heat transfer and/or interaction between fluids of different specific gravities.

3) Many pollutant transport problems involve flow, at some stage, in groundwater systems where gradients of total potential are governed by gravity.



(a)

(b)

Figure 1: Principle of Centrifuge Modelling (from Schofield, 1980): (a) prototype; (b) model

2.1 Scaling Laws

The general scaling laws that govern the relationship between the model and its corresponding prototype, with respect to the problem of hazardous waste migration, have been derived by Bachmat (1967) and Hensley (1988) using inspectoral analysis, and by Laut (1975) and Arulanandan et. al. (1988) using dimensional analysis. The relevant laws are summarised below.

$$t_p = n^2 t_m \qquad (1)$$

$$u_p = (1/n)\, u_m \qquad (2)$$

$$c_p = c_m \qquad (3)$$

where: n = scaling factor

m = model

p = prototype

u = pore fluid velocity (L/T)

t = time factor (T)

c = pollutant concentration (M/L^3)

The scaling laws were based upon assumptions that the transport of contaminant by dispersive processes would be identical in model and prototype, and that adsorption of contaminant at the fluid/particle interface would obey a rapid, linear equilibrium model. These assumptions may not be reasonable in many practical cases (Hensley and Schofield, 1991). However, a centrifuge model can always be regarded as an independent geotechnical event, producing data under repeatable and controlled laboratory conditions. Irrespective of the validity of the scaling laws, such data can therefore still be used to test and verify the mathematical modelling of transport processes.

Equation 1 states that events related to hazardous waste transport occur n^2 times faster in a centrifuge model than in the corresponding prototype. It is this feature which allows *accelerated* physical modelling of environmental engineering problems in a geotechnical centrifuge.

2.2 Verification of Scaling Laws

Verification of centrifuge scaling laws is usually carried out by performing 'modelling of models', where centrifuge models are tested at different scales and similitude between models is observed. Verification of the centrifuge scaling laws presented by Equations (1), (2) and (3), was carried out by Arulanandan et. al. (1988) at the University of California, Davis (figure 2).

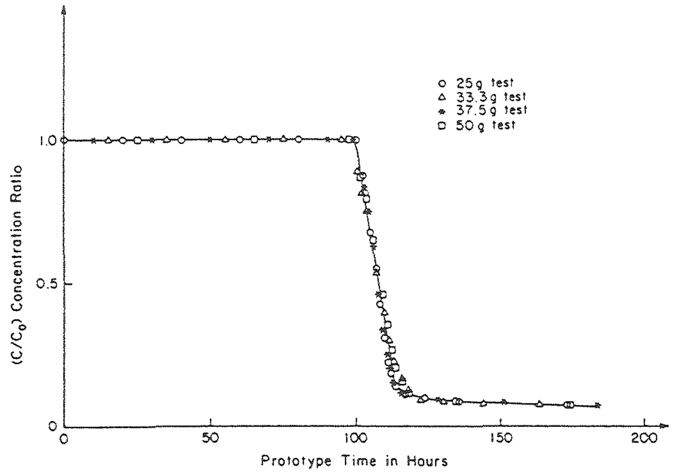


Figure 2: Verification of Scaling Laws by 'Modelling of Models' (from Arulanandan et. al., 1988)

Arulanandan et. al. concluded that the centrifuge scaling factors were correct provided that:

1. Hydrodynamic dispersion processes are identical in model and prototype.

2. Adsorption processes at the fluid-solid interface are described by rapid, linear, equilibrium laws.

3. MODELLING CONTAMINANT TRANSPORT FROM A LANDFILL SITE

The research described in this section of the Paper was conducted on the Balanced Arm Centrifuge at the University of Cambridge, England. The reader is referred to Schofield (1980) for a description of this facility.

The fundamental aim of the research was to investigate the technique of accelerated physical modelling of waste transport processes, offered by geotechnical centrifuge modelling. For this purpose, it was decided to model the migration of a single conservative pollutant species (sodium chloride) through a saturated soil deposit of finite depth.

The prototype problem chosen for the study concerned a 25 m wide, infinitely long trench of 3 m depth, sited in a 15 - 20 m deep soil deposit underlain by a permeable base stratum with horizontal groundwater flow, figure 3. Depletion of contaminant in the landfill with time was also incorporated in a number of the models.

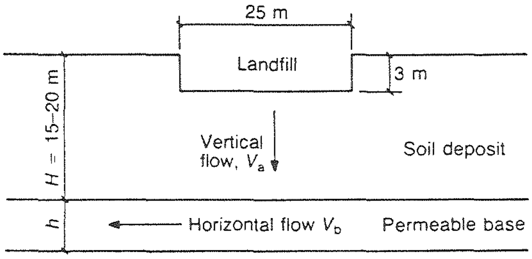


Figure 3: Prototype Problem

A standard sodium chloride solution (concentration Cl^-, 0.6 mol/dm^3) was used to represent the landfill contaminant.The principal geological deposit was formed from reconstituted 180 grade silica flour. The permeable base stratum in the model was constructed from Leighton Buzzard 25/52 sand.

A schematic representation of a typically instrumented centrifuge model is given in figure 4.

The progress of the salt-water contaminant as it moved through the soil sample was monitored by miniature four-electrode resistivity probes, that were designed and manufactured at the Cambridge University Engineering Department. These probes were also able to monitor the concentration of solution held within the landfill site. Druck miniature pore water pressure transducers were used to measure both equipotential heads within the soil body and soil surface water levels. Soil surface settlements were detected by Linear Variable Differential Transformers (LVDTs), and the temperature within the soil body was recorded by an insulated buried nickel-chrome thermocouple.

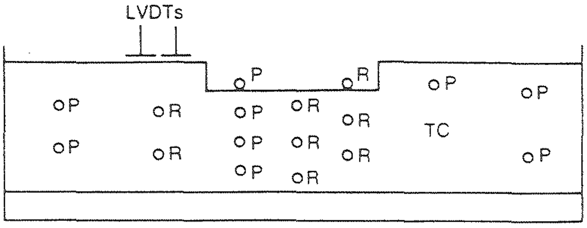


Figure 4: A Typically Instrumented Centrifuge Model: P, pore pressure transducer; R, resistivity probe; TC, thermocouple; LVDT, linear variable differential transformer

Figure 5 illustrates the service arrangements for a typical centrifuge model. The advective seepage velocity through the silt layer, and the horizontal velocity in the permeable stratum beneath the silt, were controlled by water levels within standpipes connected to the model. Alteration of standpipe overflow heights allowed for the variation of model seepage velocities between tests.

Each centrifuge test followed the same general procedure. Initially the centrifuge was started, and the speed was increased in stages to 100 gravities (100*g*). The flow pattern within the model was then established using a 'fresh' water supply to the landfill[1]. After approximately 2 hours, when the resistivity probe and pore pressure readings indicated steady state conditions within the model, the fresh water was removed from the landfill and replaced by a sodium chloride solution while the centrifuge was still in flight. For the remaining duration of the test, the landfill was supplied with either a standard sodium chloride solution, representing a constant concentration of pollutant within the landfill, or fresh water, representing a depletion of landfill pollutant concentration with time. Signals from all instrumentation were monitored throughout each test, and various events of each test were recorded by Polaroid photography.

At the end of each test, the centrifuge was stopped and a site investigation of the model was undertaken. The package was then removed from the arm of the centrifuge, and radiographed to reveal the exact location of the buried instrumentation..

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[1] Mains tap water was used to simulate a 'fresh' water supply.

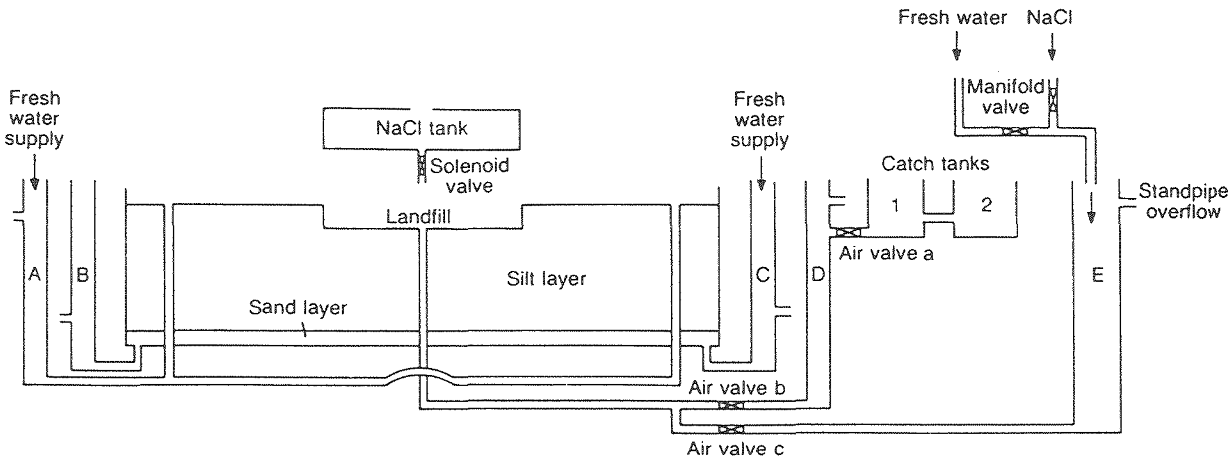

Figure 5: Schematic Diagram of Centrifuge Model

3.1 Comparison of Centrifuge Data and Theoretical Predictions

A total of seven centrifuge model tests were undertaken to study the transport of pollutants in the soil surrounding a land based waste disposal site. The model tests encompassed a number of groundwater seepage velocities and a variety of landfill boundary conditions. Results from the centrifuge tests were compared with theoretical predictions from two commercially available computer transport codes, POLLUTE and MIGRATE (Rowe and Booker 1983, 1985a and 1985b), and with analyses developed during the course of the research (Hensley, 1989, Hensley and Schofield, 1990).

The POLLUTE code uses semi-analytical techniques to solve a one-dimensional contaminant transport equation in a layered soil deposit of finite depth. The problem description for this analysis is illustrated by figure 6.

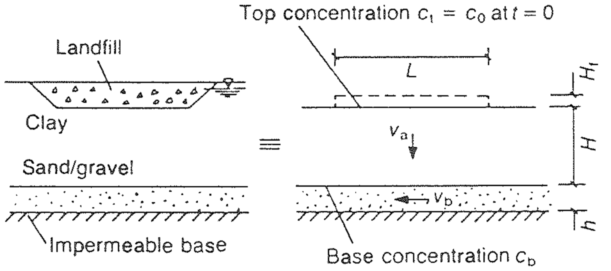

Figure 6: Problem Description for POLLUTE (from Rowe and Booker, 1985a)

In the following, a comparison of experimental data and predictions by POLLUTE is given for the fifth centrifuge test in the series, Test PJH5. The results are presented in prototype time and normalised with respect to c_S, the concentration of the model pollutant. In all figures, the theoretical data are represented by discrete points. The reader is referred to Hensley and Schofield (1991) and Hensley (1992) for a comparison of further centrifuge tests with POLLUTE and alternative theoretical analyses.

The steady state groundwater flow pattern established within model PJH5 during centrifuge flight is shown in figure 7. This seepage flow net was generated by a two-dimensional finite element program for groundwater flow, that was developed during the course of the research (Hensley, 1989).

Figure 7 clearly illustrates the two-dimensional nature of the seepage pattern established within each centrifuge model. However, this figure also demonstrates an approximately one-dimensional seepage flow pattern in the area of soil directly below each landfill site. It is therefore reasonable to expect theoretical predictions from POLLUTE to provide an agreeable estimate of the concentration rises recorded during test PJH5, at all measurement points located in the central section of the model.

Centrifuge test PJH5 modelled a landfill sited in a 14.8 m deep silt deposit, underlain by a sand deposit of 2.5 m depth. An apparent (Darcy) vertical flow velocity of 0.965 m/year was set through the soil beneath the landfill site[2], and an apparent horizontal flow velocity of 230.21 m/year was imposed along the base aquifer.

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[2] The apparent seepage velocity used in POLLUTE corresponded to the component of velocity induced by forced convection. Because the density of the model pollutant was greater than the density of the interstitial fluid, free convection would have been responsible for a component of the total convection through the model. However, the actual percentage contribution made by free convection was negligible for the conditions of test PJH5.

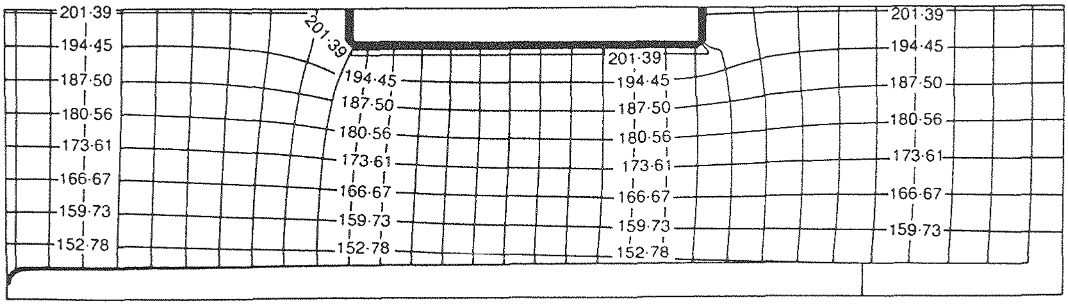

Figure 7: Steady State Seepage Net for Centrifuge Test PJH5

A comparison between theoretical and experimental data for test PJH5 is given in figure 8: Prototype dimensions and the position of appropriate measurement points are also given in this figure. The parameters required as input by the POLLUTE program were obtained from site investigation of the centrifuge model, and from independent laboratory tests.

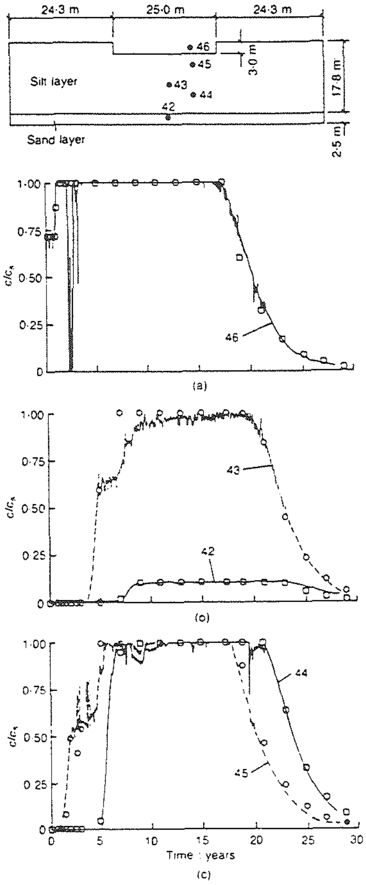

Figure 8: Measured and Predicted Concentration Changes During Test PJH5; theoretical data are represented by discrete points; (a) at probe 46 (landfill site); (b) at probes 42 (sand layer) and 43 (silt layer); (c) at probes 44 and 45 (silt layer); insert, transducer locations and prototype dimensions.

Figure 8a illustrates the concentration profile in the landfill site throughout the duration of the migration event. The landfill concentration was maintained at the maximum value, c_S, for the first 17.5 years of the migration event. Thereafter the landfill concentration was allowed to diminish with time.

Figures 8b and 8c compare experimental and theoretical data at all measurement points located directly beneath the landfill site. It is apparent from these figures, that excellent agreement was obtained between observed and predicted data at all points. Both the increase in concentration at all points during the initial stages of the test, and the decrease in concentration at these points during the latter stages of the test (when pollutant concentrations in the landfill were allowed to reduce), were well modelled by the program POLLUTE.

The magnitude of peak concentration at the probe positioned in the aquifer, probe 42, was only 10% of the maximum landfill concentration, c_S. This indicates that both the horizontal influx of fresh water along the base aquifer, and the high horizontal seepage velocity within this stratum, combined to reduce pollutant concentrations in this layer of the model.

3.2 Summary

The research presented in this section of the Paper was undertaken to investigate the technique of accelerated physical modelling of groundwater flow processes, offered by geotechnical centrifuge modelling. The centrifuge tests performed during the course of this research were the first tests of this nature to model a realistic prototype configuration on a large capacity centrifuge. These tests were shown to provide valuable data on the migration of a conservative pollutant species through the soil beneath an engineered trench site, for a wide variety of initial and boundary conditions. Prototype times of up to 30 years were modelled during the test series. Long term in-situ experiments of this nature would have been costly and extremely expensive to perform, and may have provided little direct control over boundary conditions.

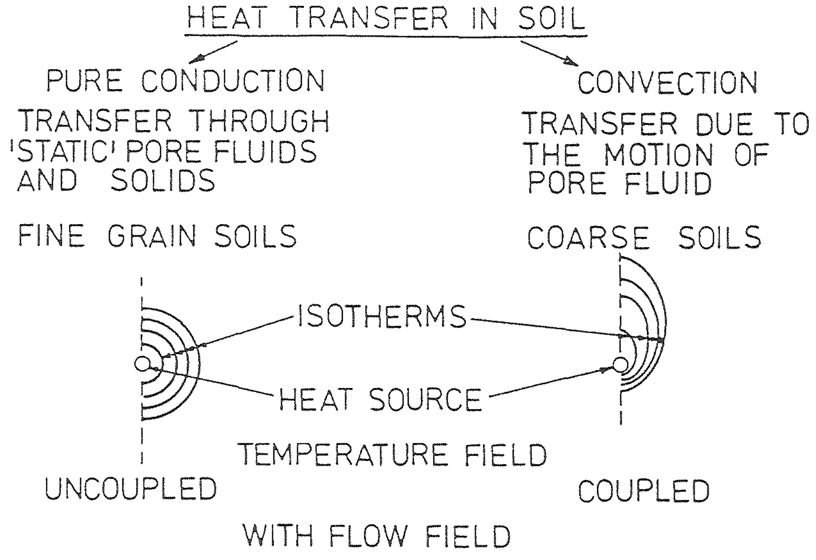

Figure 9: Heat Transfer in Soil

The centrifuge test results were compared with data from a commercially available contaminant transport code. These comparisons served to illustrate the enormous potential of a geotechnical centrifuge, in providing good quality experimental data for the verification of mathematical transport models.

4. MODELLING COUPLED HEAT AND CONTAMINANT TRANSPORT

The problem of coupled heat and contaminant transport in soils is of importance in environmental engineering problems relating to the storage and disposal of heat generating high level radioactive wastes, high temperature waste discharges from power plants and industrial processing plants, and transport processes occurring in geothermal reservoirs and thermal storage aquifers.

Heat transfer through soil may take place by pure conduction alone, in which case heat is transported through the 'static' pore fluid and through the soil particles themselves, or it can take place by convection, in which case heat transport is due to the physical motion of the pore fluid itself (Savvidou 1988), figure 9.

The transition from conductive to predominantly convective mass transfer in soil is characterised by the effective dimensionless Rayleigh Number, R_a, which symbolises the balance between the driving buoyancy force induced by convective motion, and the resistive processes of viscosity and diffusivity (Hensley and Savvidou, 1992). For centrifuge modelling techniques

$$R_{a_m} = R_{a_p} \qquad (4)$$

Equation 4 thus indicates that similarity will be achieved between a reduced scale centrifuge model and the prototype, with respect to the mechanism of combined heat and contaminant transport.

Convective transport in soil induces fluid motion in the region surrounding the waste source. Because advection is an important mechanism in many contaminant transport problems, the presence of a convective cell may well dominate the growth and spread of a pollutant plume.

The centrifuge tests described in the following, were designed to investigate mechanisms of combined heat and contaminant transport in saturated soil. These tests were conducted on the centrifuge facility at the University of Western Australia. The reader is referred to Randolph et al. (1991) for a description of this facility.

4.1 Physical Modelling and Experimental Results

The model form that was used during the study is illustrated by figure 10.

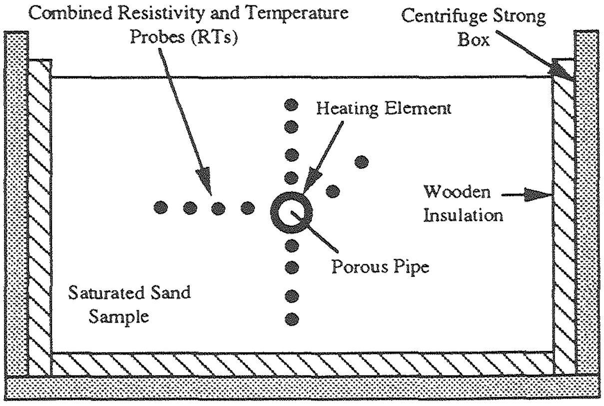

Figure 10: Model Configuration

The models were constructed from saturated silica sand, and enclosed in a rectangular centrifuge strong box. A standard sodium chloride solution (concentration Cl^-, 0.2 mol/dm^3) was introduced into each model during centrifuge flight, along a buried, horizontal porous pipe. A small positive hydraulic gradient was maintained between the pipe and the upper and lower surfaces of the model. A heating element surrounding the porous pipe allowed the temperature of the sodium chloride leaving the pipe to be raised by up to 40°C above the ambient temperature.

During each test, temperature and concentration rises in the soil surrounding the pipe were monitored by miniature combined resistivity and temperature probes. These probes comprised of two Platinum-Rubidium (Pt-Rb) wires buried in a small cylindrical core of porous ceramic material. Temperatures at the electrodes were measured by Nickel-Chrome Thermocouples, that were bonded to the base of the probes. The grain size of the ceramic material surrounding the electrodes closely matched the average particle diameter of the modelling materials used. It is therefore believed that the probes offered minimal disruption to the measured pattern of contaminant transport.

A series of eight tests was carried out to investigate coupled heat and contaminant transport in soil. These tests investigated the influence of both particle size and buoyancy effects on the transport mechanisms. The reader is referred to Hensley and Savvidou (1992) for a full discussion on the test series.

In order to illustrate the influence of buoyancy effects on heat transport mechanisms, two tests were conducted in the same sand at different *g*-levels. Results from the two tests are shown in figure 11, which presents reorded temperature rises (delta T) in the soil directly above and below the buried pipe.

Figure 11 clearly demonstrates different heat transport mechanisms at 100*g* and at 1*g*.

At 100*g*, the sensors positioned above the buried pipe registered a very sudden increase in temperature, suggesting rapid heat transport through the motion of pore fluid. However, at 1*g* the sensors above the pipe registered a slower increase in temperature, suggesting more gradual heat transport through static pore fluid and solids.

In addition, the temperature field surrounding the buried source at 100g was indicative of the 'flame shaped' isotherms associated with convective heat transfer (refer to figure 9), whereas an approximately symmetrical pattern of isotherms was observed around the source at 1g, thus intimating the presence of conductive heat transport.

The influence of convective heat transfer on contaminant transport was investigated by conducting two experiments in coarse sand at 100*g*. In the first experiment, the salt water contaminant was allowed to flow from the buried porous pipe at ambient temperature. In the second experiment, the heating element surrounding the pipe was raised to a temperature of approximately 60°C. Results from these two experiments are given in figure 12, which presents recorded concentration rises in the soil directly above and below the buried pipe.

The data shown in figure 12 explicitly illustrate the influence of convective heat transfer on contaminant transport. In the absence of heat transfer, the (dense) contaminant merely migrated to the lower region of the saturated sand model. However, in the presence of heat transfer, the contaminant was transported into both the upper and lower regions of the model.

4.2 Summary

The research presented in this section of the Paper demonstrated distinct differences in the heat transfer mechanism at 1*g* and 100*g*, and confirmed that thermally induced seepage velocities can have a major effect on the transport of contaminants in soil.

The research also served to illustrate the enormous potential of a geotechnical centrifuge, as a research tool for investigation into fundamental transport mechanisms.

5. CONCLUSIONS

This paper introduced geotechnical centrifuge modelling as an experimental method for modelling subsurface contaminant transport.

Centrifuge modelling is a technique that allows accelerated physical modelling of many contaminant transport problems, under well controlled and repeatable laboratory conditions. The usefulness of the centrifuge as a modelling tool was demonstrated by the value of data presented from two test series.

The first test series, which investigated solute migration from a land based waste disposal site, was shown to generate worthwhile data for comparison with existing transport codes.

The second test series provided valuable insight into fundamental mechanisms of combined heat and contaminant transport.

Clearly, a geotechnical centrifuge offers a very powerful testing tool for the physical investigation of many environmental engineering problems.

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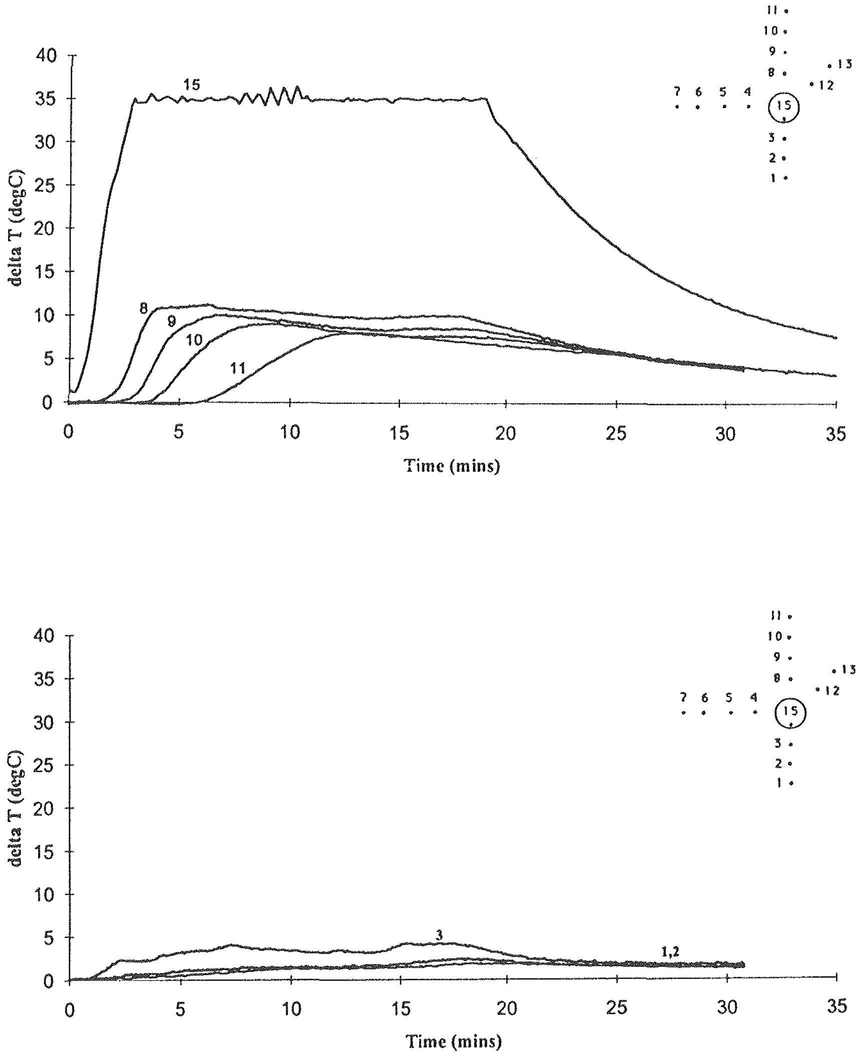

Figure 11a: Variation of Temperature Surrounding Heater with Time at 100g

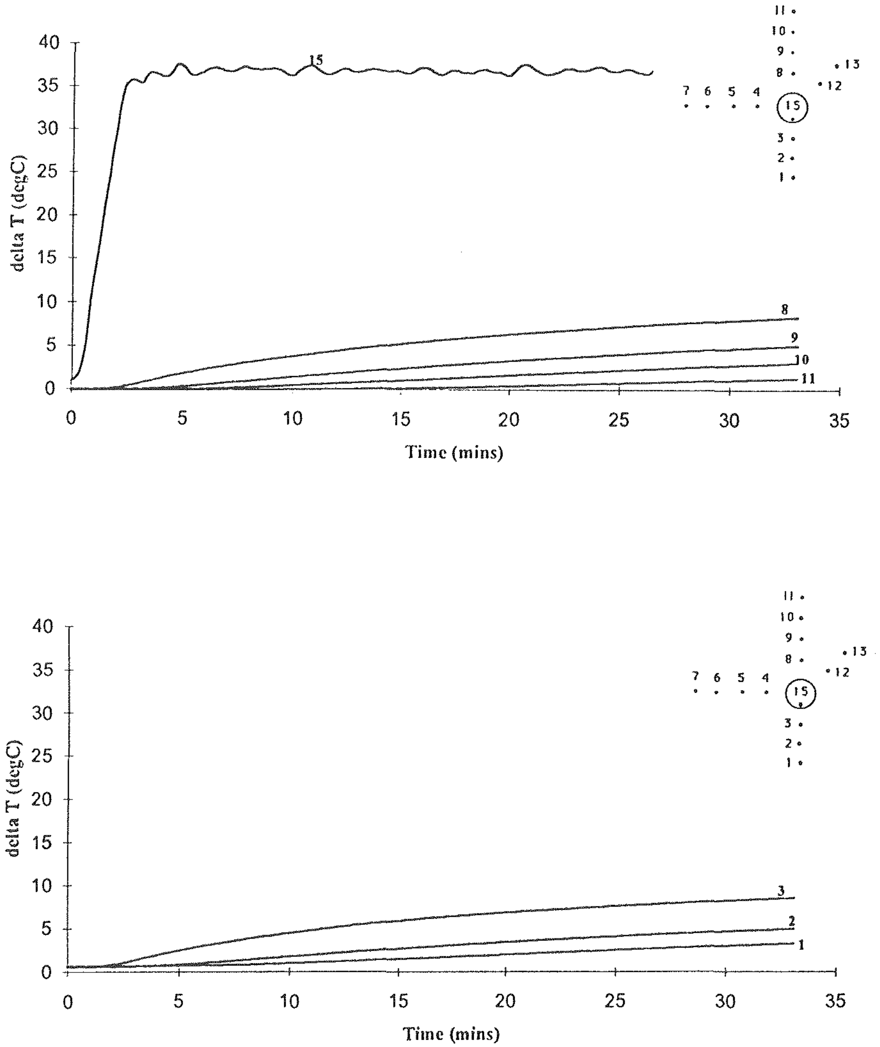

Figure 11b: Variation of Temperature Surrounding Heater with Time at 1g

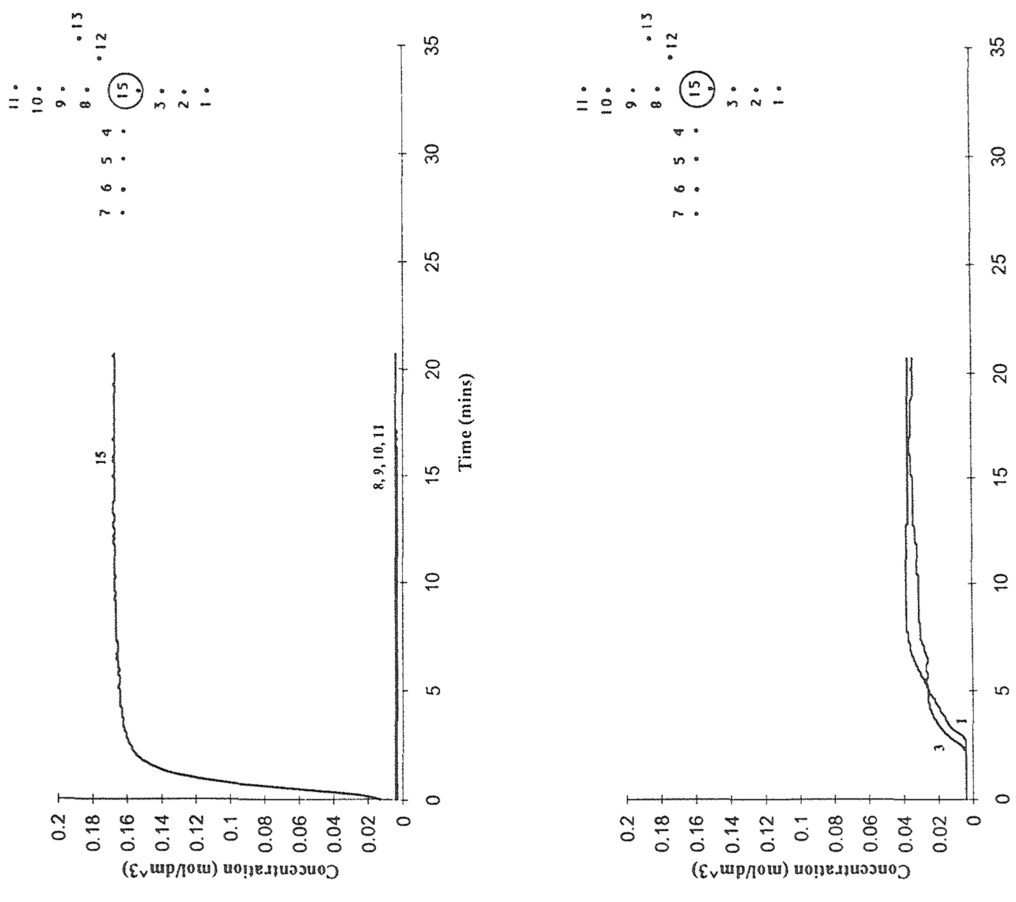

Figure 12a: Concentration Rises Recorded in the Absence of Heat Transfer

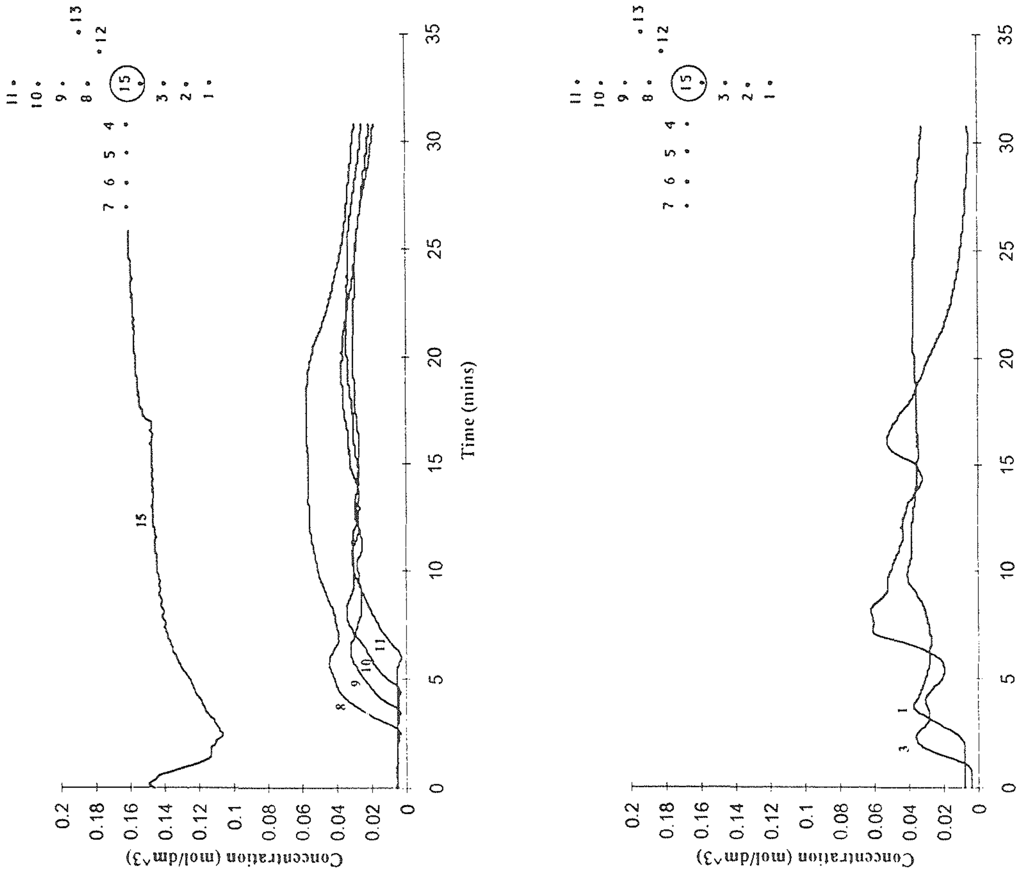

Figure 12b: Concentration Rises Recorded in the Presence of Heat Transfer

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