A STUDY OF CONTAMINANT TRANSPORT INVOLVING DENSITY DRIVEN FLOW AND HYDRODYNAMIC CLEAN UP

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A study of contaminant transport involving density driven flow and hydrodynamic clean up

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ABSTRACT: This paper describes an experiment performed on the Cambridge Geotechnical Centrifuge investigating the migration of a contaminant plume under the influence of density gradients. The conceptual prototype was a landfill leaking a non-sorbing dense pollutant into a homogeneous silt layer. The formation of the plume was followed by clean up using hydrodynamic techniques. The concentration of pollutant throughout the soil was monitored by miniature insitu resistivity probes.

The work demonstrates the effectiveness of the geotechnical centrifuge in modelling transport processes involving dense pollutants. This paper presents the theory governing the transport of a dense pollutant through soil, outlines the relevant scaling laws, describes a typical centrifuge test and compares the results with a numerical prediction.

1. INTRODUCTION

Contamination of groundwater is an issue of major concern in residential areas in the vicinity of landfills and waste disposal repositories. The extent of contamination and the mechanisms responsible for the transportation of contaminants in the underlying groundwater system is a central issue in cases where municipal water supplies depend on the utilisation of the groundwater resources.

It has recently become apparent that there is a lack of physical observations of pollutant behaviour in soils. This information is vital to evaluate existing theoretical models and develop improved conceptual models of transport processes. The high costs, large time scales and lack of control over the boundary conditions have prevented the development of field scale experiments. Column tests are of limited use and difficult to apply to full scale problems. Thus researchers have recently come to recognise that a geotechnical centrifuge can provide a powerful testing tool for modelling the transport of contaminants in soils (Hensley 1989, Cooke and Mitchell 1991, Hensley and Savvidou 1993, Hellawell et al 1993).

The research presented in this paper investigated the transport of a non-sorbing dense pollutant from a landfill into a homogeneous saturated silt layer and the subsequent hydrodynamic clean up. The results of the tests were compared with theoretical predictions from the finite difference computer code HST3D (Kipp 1987).

2. THEORY

Contaminant transport in porous media can be described by the conservation of **fluid** mass and contaminant mass in the macroscopic continuum. A comprehensive review of the governing equations can be found in Hensley and Sawidou 1993. The equations are linked through the coupling of velocity, density and viscosity terms and their dependence on fluid pressure and contaminant mass fractions. Fluid density is assumed to be a linear function of pressure and contaminant concentration over the ranges of these parameters encountered in this paper. Thus

$$\rho(p,w)=\rho_o+\rho_o\beta_p(p-p_o)+\rho_o\beta_w(w-w_o) \qquad [1]$$

where po is the density at the reference pressure $p_O$and mass fraction w_O, β_p is the fluid compressibility and β_W is the slope of the fluid density as a function of mass fraction, divided by the reference fluid density.

Darcy's law in one-dimensional form describes fluid motion as the sum of two convective terms: a) piezometric head differences and b) density gradients causing free convection..

$$u_z=-\frac{k}{n\mu}\rho_o g\frac{\partial}{\partial z}\left(\frac{p}{\rho_o g}+z\right)-\frac{kg(\rho-\rho_o)}{n\mu} \qquad [2]$$

The vertical direction of fluid motion due to free convection depends on the arrangement of the different density fluids.

The dominant convective mechanism is determined by the ratio of the forced and free convection terms (Bear 1972).

$$R = \frac{|\Delta\rho / \rho_o|}{|\Delta\phi_o / L|} \qquad [3]$$

where Ap = ρ – po, ϕ_0 = (p / ρ_0g + z) and L is the characteristic macroscopic length of the system.

Stable equilibrium of the system may be obtained even if the density gradient increases vertically upwards due to the damping effects of viscous resistance and diffusivity. This occurs provided the density gradient has not exceeded a critical value. The 'solute' Rayleigh number derived by Wooding (1959) determines the ratio between the driving buoyancy force and two resistive processes.

$$R_{as} = \frac{\frac{\partial w}{\partial z} gkH^2\beta_w}{D_d^* \nu} \qquad [4]$$

where $\partial w / \partial z$ is the vertical concentration gradient at any given z, Dd* is the effective diffusion coefficient, ν is the kinematic viscosity of the fluid and H is a typical linear dimension of the problem. At a critical value of the solute Rayleigh number buoyancy forces dominant and contaminant migration will occur. (Wooding 1959, Neild 1967)

3. CENTRIFUGE MODELLING

The simulation of identical effective stress states in scaled centrifuge model and equivilant prototype ensures the modelling of soil properties including hydraulic conductivity. Centrifuge modelling is particularly applicable in replicating the physical transport of dense pollutants due to gravitational gradients. The increased acceleration field is essential to correctly study such phenomena in reduced scale models (Savvidou and Hensley 1992 ,1993).

3.1 Scaling Laws

The correct scaling of physical parameters relating to contaminant transport is essential for similitude of these processes in the centrifuge model and prototype. Dimensional analysis (Laut 1975, Arulanadan et al 1988) and inspectoral techniques (Bachmat 1967, Hensley 1988) have been used to derive the general scaling laws for centrifuge modelling of contaminant migration. The relevant laws are

$$t_p = n^2 t_m \qquad [5]$$

$$u_p = \frac{1}{n} u_m$$

$$c_p = c_m$$

where n is the scaling factor, u is the pore fluid velocity (L/T) , t is the time factor (T), c is the concentration of pollutant (M/L^3) and m and p symbolise the model and prototype respectively.

These laws assume that the dispersive processes are identical in model and prototype, and the adsorption of contaminant obeys a rapid linear equilibrium model. These assumptions are applicable to this study where dispersion does not dominate and a non -sorbing contaminant is used.

If the same pollutant is used in the model and prototype ensuring that $\rho_m = \rho_p$ and $\mu_m = \mu_p$. For density driven flow it is also important to consider the replication of potential hydraulic instability . Hensley and Savvidou (1993) recently showed that

$$R_{as_p} = R_{as_m} \qquad [6]$$

which reinforces the argument for the need for the accelerated gravitational field in a reduced scale model.

3.2 Centrifuge test

The prototype considered was a 10m wide landfill leaking dense pollutant through its base into a homogeneous soil layer (figure 1). The level of fluid in the landfill was constant at the same height as the water table in the surrounding soil. Two sampling wells were positioned 28m apart on either side of the landfill.

The soil used was 180 grade silica flour mixed under vacuum to 40% moisture content. 1M sodium chloride solution was used as the model pollutant. Miniature 4 pin resistivity probes designed and manufactured at CUED monitored the progress of the contaminant plume through the soil. These were calibrated in the laboratory in soils samples prepared in the similar manner to the tests containing known concentrations of sodium chloride. The accuracy of the resistivity measurement at these high saline concentrations was achieved by increasing the supply current and the signal amplification.

Thermocouples were attached to the resistivity probes to record variations of the soil temperature. Other instrumentation included Druck miniature pore water pressure transducers buried in the model and a linear variable differential transformer (LVDT) recording the settlement of the landfill.

The wells were constructed from moulded vyon and filled with coarse sand. They were supplied with fresh water from two standpipes attached to the package. Figure 2 illustrates the service arrangements for the test. Initially air valve B was shut and thus the water level in the wells and package was constant. A wave gauge determined the fluid depth in the landfill. A control loop from the gauge signal operated a peristaltic pump and solenoid valve which controlled the contaminant supply from an overhead reservoir. Thus constant fluid head in the landfill was maintained automatically.

Initially the centrifuge was started with a small amount of contaminant in the landfill. The speed was increased in stages to 100 gravities. The control loop operating the feed of pollutant to the landfill was then switched on and the landfill filled to the set height with contaminant. The sample consolidated under self weight and after about 15 minutes the pore water pressure had reached equilibrium.

Once the plume was created, valve B was opened and the clean up phase begun. The plumbing of alternate high and low overflows caused a hydraulic gradient to be established between the two wells. Ball valve A enabled flow reversal during clean up.

The test was performed at 100g with plume creation lasting, at model time, approximately 26.5 hours followed by 5 hours of clean up. The instrumentation was monitored throughout the test recording the development of the contaminant plume. After the end of the test the centrifuge was stopped and the model inspected. The soil was then X-rayed and finally excavated to reveal the position of each probe.

4. COMPARISON BETWEEN CENTRIFUGE TEST DATA AND THEORETICAL PREDICTIONS

The results from the centrifuge test were compared with theoretical predictions using computer code HST3D (Heat and Solute Transport in 3 Dimensions). The program uses finite difference techniques and can be adapted to consider isothermal density driven flow in 2 dimensions (Kipp 1989). In this form the program solves the saturated groundwater equation (formed from the conservation of fluid mass and Darcy's law) and the solute transport equation. The equations are linked through velocity density and viscosity coupling terms. Table I summarises the input parameters which were determined by laboratory tests. Prototype test values are considered and all results are presented in prototype test times.

The very low dispersivities representative for the homogeneous silty soil used in the centrifuge test caused difficulties in obtaining an accurate numerical solution. Trials using various differencing techniques, larger dispersivities and mesh refinements were performed in an effort to instability and numerical dispersion errors. Figure 3 presents a comparison of solutions for the movement of a concentration front at a point below the landfill. It was concluded that a solution using forward differencing in time with backward differencing in space with a 55x45 node mesh minimised the numerical dispersion and produced the optimum results. All theoretical solutions presented here have been produced in this manner.

Table I includes values for the solute Rayleigh numbers, which exceed the critical value of 27.1 suggested by Neild (1967) for porous/impermeable boundary conditions. Thus buoyancy forces dominated resulting in density driven contaminant migration.

At the start of the test the concentration of contaminant in the landfill varied as the short period of consolidation (caused dilution of the solute. Thus the program was run in two stages with the landfill contaminant concentration set to the average value for that time period. HST3D considers a rigid porous matrix and therefore does not take into account consolidation:. However this is fairly insignificant in the silt model where equilibrium was achieved shortly after the start of the test.

A comparison between the theoretical and measured contaminant front migration and later clean up at four positions in the soil model is shown in figure 4. Probes 3 and 6 lie at almost the same depth, yet the latter detected the plume first. This can be explained by contour plots showing the predicted progress of the plume after 10.5 and 30 years (figure 5). The contaminant travels further at the edges of the landfill than beneath its centre. The plume is also predicted to show greater dispersion at the edges of the landfill where the contour spacing increases. A comparison of concentration profiles measured at the probes shows good agreement with this prediction.

The clean up phase was started about 26.5 hours (30 years of prototype time) after the initial leakage of dense pollutant. A hydraulic gradient was initially imposed to flush the plume towards well 2. However a blockage occurred in a standpipe overflow, thus the flow was reversed after 0.6 hours. The contaminant plume was then flushed towards well 1 for the remaining 5 hours of the test. All stages followed in the test were considered in the input to the numerical program.

The movement of the plume during clean up is shown by the effects of the flushing on probes 7, 3 and 5. At the end of the test probe 3 is beginning to detect the clean front, whereas high concentrations of contaminant are being detected at probe 5. Thus after 5.7 years of pumping, half the site is clean. Probe 7 showed a larger variation between the predicted and measured values. This is probably due to a lateral error in the positioning of the probe.

Reasonable agreement is obtained between the theoretical and measured values during the plume creation and clean up phases. The slight discrepancy in the slopes of the curves can be attributed to small numerical dispersion.

5. CONCLUSIONS

The geotechnical centrifuge was used for modelling the migration of dense pollutants from a landfill. The accelerated gravity field enables correct scaling of density gradients in the reduced scale model.

The solute Rayleigh number implyed that density forces were dominant over any viscous forces. Hydraulic instability occurred between the pollutant and saturated porous media resulting in density driven flow.

The hydrodynamic clean up of a dense contaminant plume was demonstrated. Although a high hydraulic gradient was imposed between the wells, at prototype time of 5 years after pumping only half the site was clean. The results highlight that hydrodynamic clean up is not satisfactory except in highly permeable soils.

Reasonable agreement was obtained between the theoretical model HST3D predictions and the centrifuge test results for both the plume development and clean up processes.

6. REFERENCES

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Parameter Description	Value
Porous medium porosity	0.45
Hydraulic conductivity	2.3x10-7 m/s
Longitudinal dispersivity	3.26x10-4 m
Transverse dispersivity	$3.26\text{x}10^{-5}$m
c_{well} (O-10.5 yrs)	0.6675 M
c_{well} (10.5-30 yrs)	1.0 M
P pore fluid	998.62 Kg/m3
P contaminant (1M)	1041.9 Kg/m3
μ pore fluid	1.001x10-3 Kg/m
μ contaminant(1M)	1.087x10-3 Kg/m
D_d^*	$7.3\text{x}10^{-10}$ m^2/s
R_{as} (1-10.5)yrs)	167.5
R_{as}(10.5-30yrs)	250.8
Isothermal temperature	18°C
Clean up	
Hydraulic gradient	
(0 -0.68yrs)	0.02 1
(0.68 - 5.7yrs)	0.125

Table I • parametric values for analysis

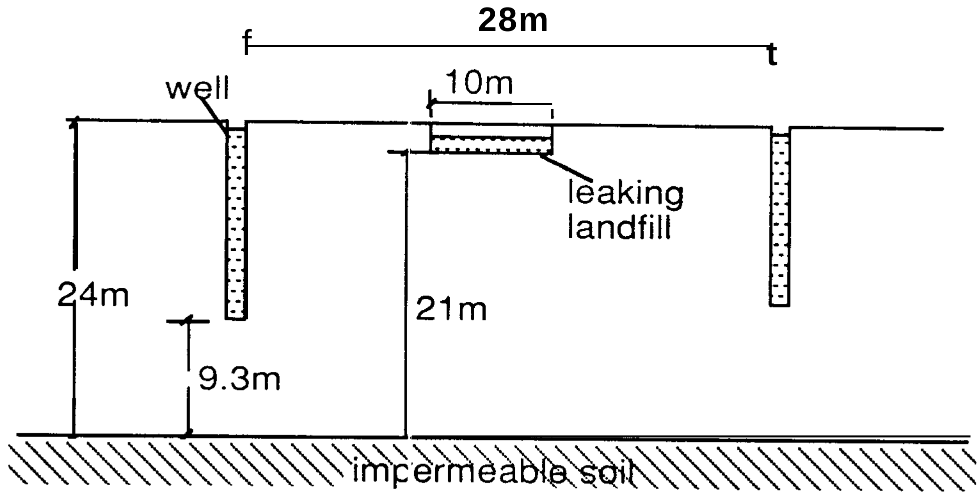

Figure 1 - Prototype of centrifuge test

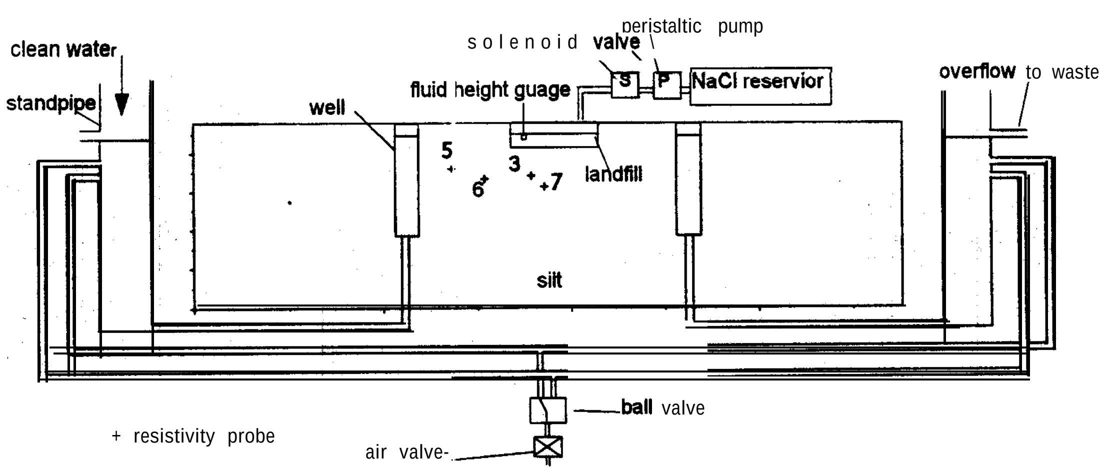

Figure 2 - Centrifuge model service arrangements

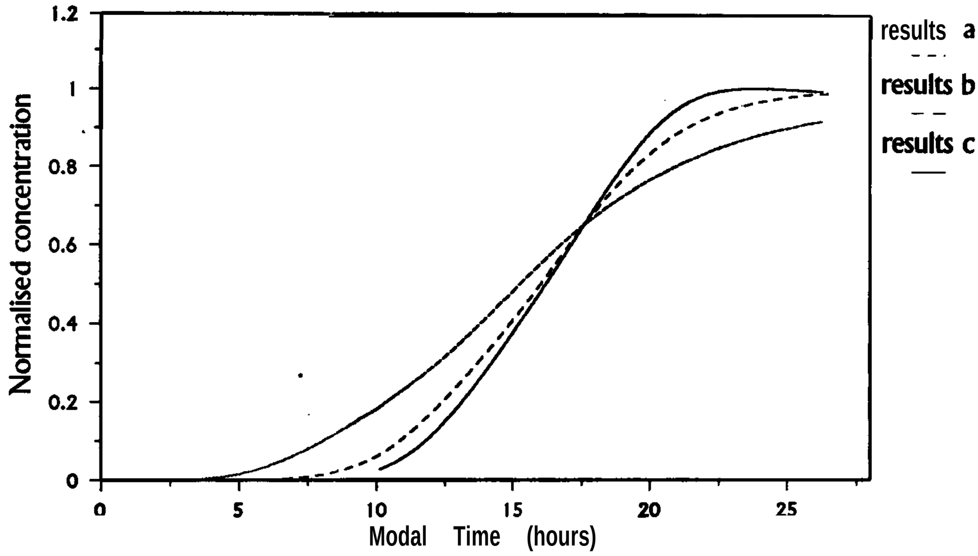

Figure 3- Comparison of **finite** difference solutions, a) forward difference in time and backward difference in space, b) centre difference in time and space, c) centre difference in time and space with longitudinal dispersion **coefficient** = **0.326m**

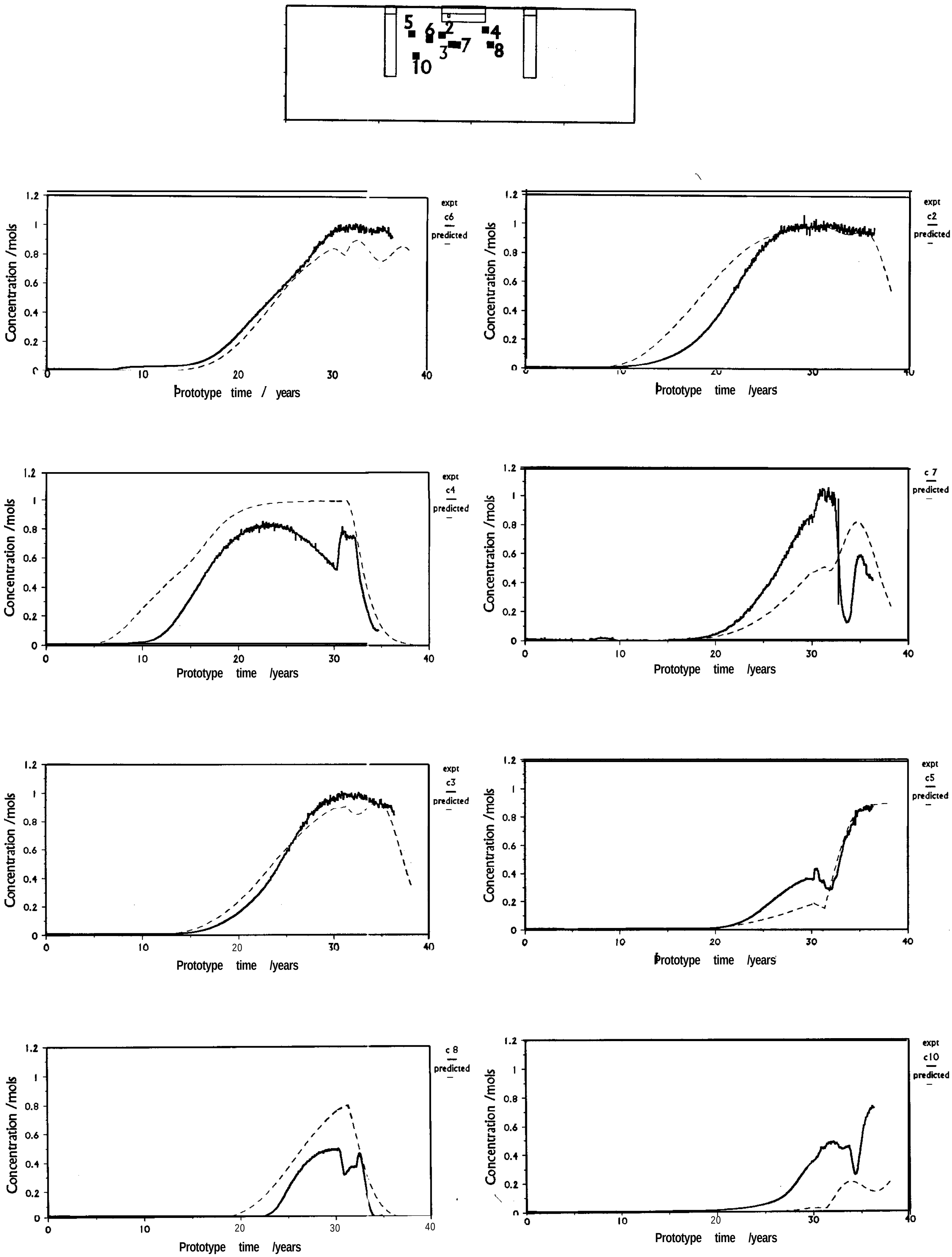

Figure 4: comparison of centrifuge test data with predictive HST3D model

a) 10.5

b) 30 years.

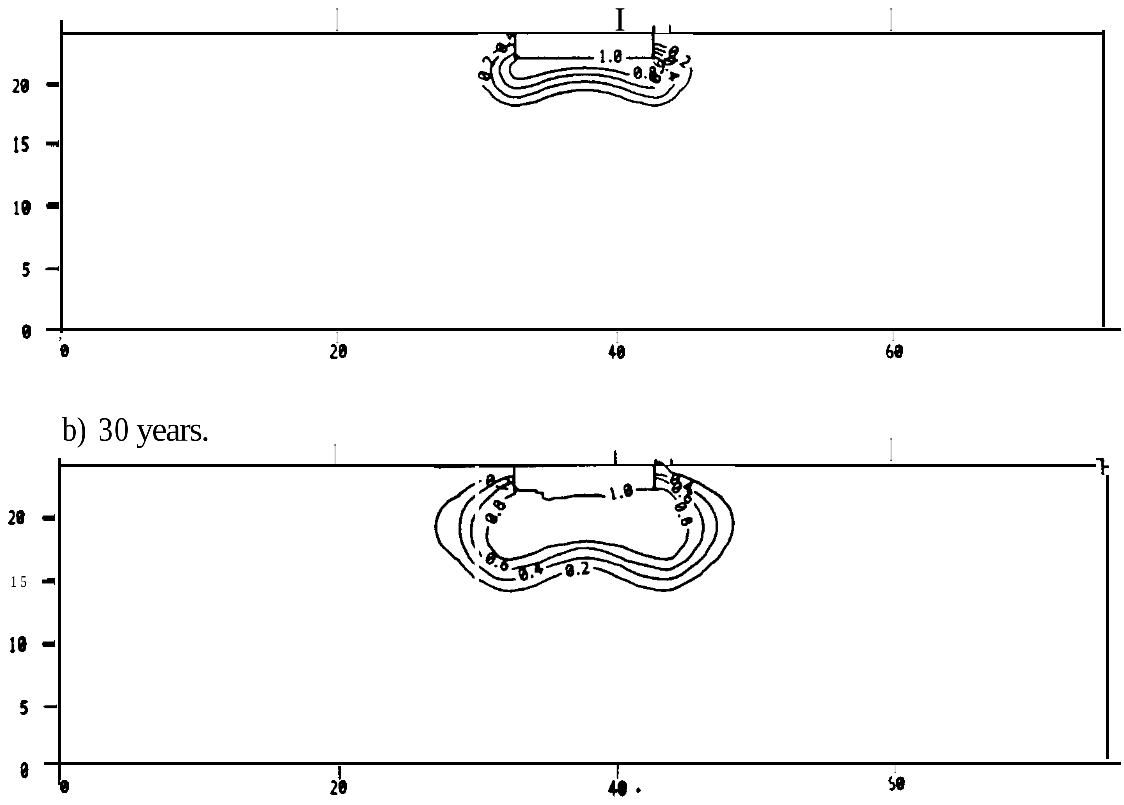

Figure 5 • Predicted progress of the contaminant plume after a) 10.5 and b) 30 years.