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by

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CUED/D - SOILS /TR.301 (1996)



# Modelling the transport of a pulse of two contaminants through a clay layer

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## INTRODUCTION

Physical observation of phenomena related to groundwater contamination are rare and difficult to obtain from field experiments. Geotechnical centrifuges can produce representative deformation and transport behaviour in scale models (Schofield, 1980). Gronow *et al.* (1988) and Evans *et al.* (1994) have demonstrated the use of drum centrifuge geotechnical modelling for contaminant transport problems.

An experimental investigation of the one-dimensional migration of a fixed duration pulse of two contaminants down through a clay layer is reported. Centrifuge tests **BAP1** and **BAP2** were conducted at **100g** and **150g** respectively, using the Mark II **Minidrum** Centrifuge. The rates of simultaneous migration and dispersion of an aqueous organic and an aqueous inorganic contaminant were studied.

## THEORY

For one-dimensional vertical contaminant transport accompanied by linear sorption in a uniform soil under a constant hydraulic gradient the variation of concentration  $c$  with time  $t$  and depth  $z$  is governed by the advection-dispersion equation:

$$\frac{\partial c}{\partial t} = \left( \frac{D_l}{R_d} \right) \frac{\partial^2 c}{\partial z^2} - \left( \frac{\bar{v}}{R_d} \right) \frac{\partial c}{\partial z} \quad (1)$$

where  $D_l$  is the longitudinal hydrodynamic dispersion coefficient,  $R_d$  is the retardation factor of the contaminant compared with the water flow and  $\bar{v}$  is the mean pore fluid velocity (see Domenico & Schwartz, 1990, for example). The hydrodynamic dispersion coefficient depends on both the dispersive and diffusive aspects of contaminant movement:

$$D_l = D_d^* + D \quad (2)$$

where  $D_d^* = \tau D_d$  is the effective diffusion coefficient,  $D = \alpha_l \bar{v}$  the mechanical dispersion coefficient,  $\tau$  the tortuosity,  $D_d$  the free solution diffusion coefficient and  $\alpha$ , the dispersivity.

If the soil is subjected to a pulse input of contaminant such that the surface concentration is  $c_0$  for  $0 < t \leq t_0$  and zero for  $t > t_0$ , and equation (1) applies, then the boundary conditions are mathematically equivalent to the superposition of the case where  $c = c_0$  for  $t > 0$  and the case

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where  $c = -c_0$  for  $t > t_0$ . The concentration variation can be found directly using the analytical result of Ogata & Banks (1961) and is therefore:

$$\frac{c}{c_0} = \frac{1}{2} \left[ \operatorname{erfc} \left( \frac{z - \frac{\bar{v}}{R_d} t}{\sqrt{4 \frac{D_l}{R_d} t}} \right) + \exp \left( \frac{z \bar{v}}{D_l} \right) \operatorname{erfc} \left( \frac{z + \frac{\bar{v}}{R_d} t}{\sqrt{4 \frac{D_l}{R_d} t}} \right) \right]$$

$$- \frac{1}{2} \left[ \operatorname{erfc} \left( \frac{z - \frac{\bar{v}}{R_d} (t - t_0)}{\sqrt{4 \frac{D_l}{R_d} (t - t_0)}} \right) + \exp \left( \frac{z \bar{v}}{D_l} \right) \operatorname{erfc} \left( \frac{z + \frac{\bar{v}}{R_d} (t - t_0)}{\sqrt{4 \frac{D_l}{R_d} (t - t_0)}} \right) \right] \quad (3)$$

which can be matched to experimental plume data to estimate the transport parameters.

In clay, when the dominant dispersive mechanism is diffusion, the centrifuge scaling laws state that for a model accelerated at  $N$  gravities the ratios of model to prototype (a full scale body in the Earth's gravitational field) are  $N$ : 1 for acceleration,  $1$ :  $N$  for depth, and  $1$ :  $N^2$  for time (Arulanandan *et al.*, 1984; Hensley, 1989). Physical modelling of contaminant transport over decades in the field can therefore be done in a matter of hours using the geotechnical centrifuge.

#### APPARATUS AND MATERIALS

The tests were done using the University of Cambridge Department of Engineering's Mark II Minidrum Centrifuge, shown in Fig. 1. This machine is a twin concentric shaft design and is a development of the one described in Evans *et al.* (1994). Fig. 2 is a section diagram of the minidrum showing the arrangement of the twin concentric shafts, and the use of a slurry spreader for model construction. No instrumentation was used in the first minidrum model, but resistivity probes were embedded in the soil in the second model to give an in-flight indication of the migration of the inorganic plume. A PC-based data collection system was used to monitor these probes.

E-grade kaolin was used as the porous medium through which the contaminant was leached. E-grade kaolin is a very coarse white china clay with a mean particle size by weight of  $5\mu\text{m}$  and a clay content of 25% (Elmes, 1985). Deionised water was used in the preparation of the models and solutions. Sodium chloride, a safe but typical municipal landfill pollutant, was used at a concentration of  $0.1\text{mol/L}$  as the inorganic contaminant and food dyes were chosen as the organic contaminants since they also pose no health risks and would give a qualitative as well as a quantitative indication of the plume. A red, cochineal-based dye was used in the first

centrifuge run and, following simple tests to estimate the degree of sorption on to kaolin, a yellow, tartrazine-based dye in the second.

#### MODEL CONSTRUCTION AND EXPERIMENTAL PROCEDURE

A **schematic** of the **minidrum** model is shown in Fig. 3. The clay model sits on top of a free-draining base layer and a downward hydraulic gradient is imposed. The first model was made using the technique developed with the Mark I **Minidrum Centrifuge**, with the **centrifuge** axis horizontal and the drive shaft rotating at **155rpm**. An 8mm base drain of sand was **poured** into the channel while its axis was horizontal and rotating at 155rpm. This drain consisted of coarse (14 / 25) overlain by finer (25 / 52) Leighton Buzzard sand. The sand drain was then smoothed with a paddle and saturated with deionised water. Kaolin slurry mixed to a moisture content of 100% was then poured into the channel in stages until the channel was full. The drive shaft was returned to its vertical position, the speed was increased and the clay consolidated to **100g** at 537rpm (acceleration measured **55mm** from the base of the channel) for 4 hours and 40 minutes. A downwards hydraulic gradient during consolidation prevented formation of pock marks (Evans et **al.**, 1994). The final thickness of the clay layer was 60mm. With the channel rotating contaminant solution was introduced on to the surface and leached for 2 hours and 20 minutes, followed by deionised water for 1 hour and 18 minutes, at **100g**. **10mm** of fluid was maintained at the surface by manual addition.

The second model was made using an improved technique making use of the twin concentric shaft available in the Mark II **Minidrum** Centrifuge. The mounting of the resistivity probe supports against the base of the channel precluded the smoothing of a sand drain with the paddle, so a 6mm thick geotextile mat was used for the base drain instead. This was glued to the base of the channel, with a perforated pipe at one edge to maintain drainage in the event of the geotextile blocking. A slurry spreader supported on the central concentric shaft was used to place the clay with the drive shaft vertical and rotating at **155rpm** and the twin shaft slowly rotating relative to the drive shaft. After slow initial stages of consolidation to avoid pock mark formation (Evans, 1994) the model was consolidated to 150g for 4 hours and 20 minutes. The final thickness of the clay layer was **55mm**. The contaminant solution was introduced on to the surface and leached for 2 hours and 33 minutes, followed by deionised water for 3 hours and 8 minutes, at 150g. Again, **10mm** of fluid was maintained at the surface by manual addition.

After each test a profiler was used to shave off a series of 1mm thick samples from around the cylindrical surface of the kaolin. The samples were stored in polypropylene pots prior to laboratory analysis and care was taken to avoid cross-contamination between the layers. A moisture content determination was made on a portion of each sample and pore water extracted from the remainder with a small laboratory centrifuge. The sodium ion content in the pore water **samples** was determined using an Atomic Absorption Spectrometer and the organic dye content was determined using a UV-vis **Spectrophotometer**.

Kaolin has a low ion exchange capacity (Ferris & Jepson, 1975) and the short duration of the experiment means that the ion exchange reactions are unlikely to reach equilibrium. The sodium chloride is therefore regarded as an unretarded tracer, so  $D$ , and  $\bar{v}$  in equation (3) were estimated for each test by manually matching the position and spread of the theoretical plume to that observed in the model, assuming  $R_d = 1.0$  for sodium. Taking  $\tau = 0.4$  for kaolin (Shackelford & Daniel, 1991) and  $D_d = 1.33 \times 10^{-9} \text{ m}^2 / \text{s}$  for Na<sup>+</sup> (Atkins, 1994) gives  $D_d^* = 0.5 \times 10^{-9} \text{ m}^2 / \text{s}$ , and substituting into equation (2), the dispersivity  $a$ , was then calculated. The hydraulic conductivity  $k$  and a second, approximate value for  $\bar{v}$  was estimated from the total water flux and the mean moisture content  $w_{av}$ .

## RESULTS AND DISCUSSION

For test **BAP1**, which modelled a 6m thick clay layer, the moisture content ranged from 0.66 at the clay surface to 0.46 just above the sand drain with  $w_{av} = 0.52$ . For test **BAP2**, which modelled an 8.25m thick layer, it varied from 0.67 to 0.47 with  $w_{av} = 0.514$ . This reflects the prototype's increased effective stress with depth.

The normalised concentration profiles, plotted at prototype scale in Fig. 4 for test **BAP1** and in Fig. 5 for test **BAP2**, show clear separation of the organic and inorganic plumes. They also show a greater spread at the leading edge of the plume, which will be due partly to the increased time available for dispersion of this part of the plume and partly to the reduction in porosity and therefore increase in  $\bar{v}$  with depth. This latter effect could not be simulated in a simple lg laboratory column test, which would in any case require more complex loading and pressuring apparatus. Characterising the front of a contaminant plume as the point at which  $c = 0.5c_0$ , the fronts of the organic and inorganic plumes were found to reach the depths given in Table 1 in the total leaching times shown. Comparison of the total sodium ion content in the samples with the amount supplied to the model indicates 99.8% recovery in test **BAP1** and 70.9% recovery in test **BAP2**. At present no satisfactory explanation can be given for the discrepancy in test **BAP2**.

Figs. 6 and 7 show the experimental sodium plumes plotted against model depth, and the matched curves; in Fig. 7 the lower curve corresponds to the theoretical curve with an input concentration equal to  $0.7c_0$ . In each test it was possible to match the theoretical profile with the experimental one very satisfactorily, assuming that the two contaminants did not interact and therefore that they migrated independently.

The estimated transport parameters are listed in Table 2. There is close agreement between the two values of  $\bar{v}$  for each test, which indicates that the treatment of the sodium as a conservative tracer is correct, and the hydraulic conductivity is consistent with the value of  $4 \times 10^{-9} \text{ m} / \text{s}$  measured by Hensley (1989) for E-grade kaolin at a moisture content of 0.4. The dispersivity is two orders of magnitude larger than the mean particle size, which is surprisingly high, and

indicates that mechanical dispersion accounts for **70%** and **80%** of the total **dispersion in tests BAP1** and **BAP2** respectively at model scale, but only **2.5%** at prototype scale.

The organic dyes were clearly retarded, tending to stick to the top of models where the peak concentrations were 160% of the input concentration for the red dye and 210% for the yellow dye. The retardation factors of the organic dyes, calculated as the ratio of the penetration depth of the dye plume to that of the sodium, are **7.5** for the cochineal and **8.2** for the tartrazine. Given the narrowness of the dye plumes and the shortness of the test, these are likely to be underestimates of  $R_d$ .

## CONCLUSIONS

The one-dimensional leaching of two contaminants simultaneously through an E-grade kaolin clay layer was successfully **modelled** in the twin concentric shaft **minidrum** centrifuge, with post-test sampling showing a clear separation of the inorganic contaminant (sodium chloride) and the organic contaminant (food dye) plumes. Mechanical dispersion in the prototype would be insignificant, but accounted for **70–80%** of the dispersion in the model. These two tests show that this class of centrifuge testing holds good prospects for the experimental study and measurement of contaminant transport processes in fine-grained soils.

## ACKNOWLEDGEMENTS

The tests reported in this paper were performed as part of the second author's final year Master of Engineering research project. The authors wish to thank Mr. Chris Collison and Dr. Rod Lynch for their assistance.

## NOTATION

$c$	contaminant concentration
$c_0$	input contaminant pulse concentration
$D$	mechanical dispersion coefficient
$D_d$	free solution diffusion coefficient
$D_d^*$	effective diffusion coefficient
$D_l$	longitudinal hydrodynamic dispersion coefficient
$k$	hydraulic conductivity
$R_d$	contaminant retardation factor
$t$	time
$t_0$	input contaminant pulse duration
$\bar{v}$	mean pore fluid velocity
$w_{av}$	mean moisture content
$z$	depth

$\alpha_l$  longitudinal dispersivity  
 $\tau$  tortuosity



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TABLES

Table 1. Depths reached by  $c = 0.5c_0$  points on plume

Test	Model $t$	Model depth: m		Prototype $t$	Prototype depth: m	
		inorganic	organic		inorganic	organic
BAP1	3hr 38min	0.0248	0.0033	4.15yr	2.48	0.33
BAP2	5hr 41min	0.0379	0.0046	14.6yr	5.69	0.68

Table 2. Calculated transport parameters for model

Test	$w_{av}$	$\bar{v}$ : m / s		$D_i$ : $m^2 / s$	$k$ : m/s	$\alpha_i$ : m
		Water flux	Plume match			
BAP1	0.520	$2.5 \times 10^{-6}$	$1.9 \times 10^{-6}$	$1.7 \times 10^{-9}$	$12 \times 10^{-9}$	$0.6 \times 10^{-3}$
BAP2	0.514	$1.9 \times 10^{-6}$	$2.0 \times 10^{-6}$	$2.7 \times 10^{-9}$	$6 \times 10^{-9}$	$1.1 \times 10^{-3}$

FIGURES

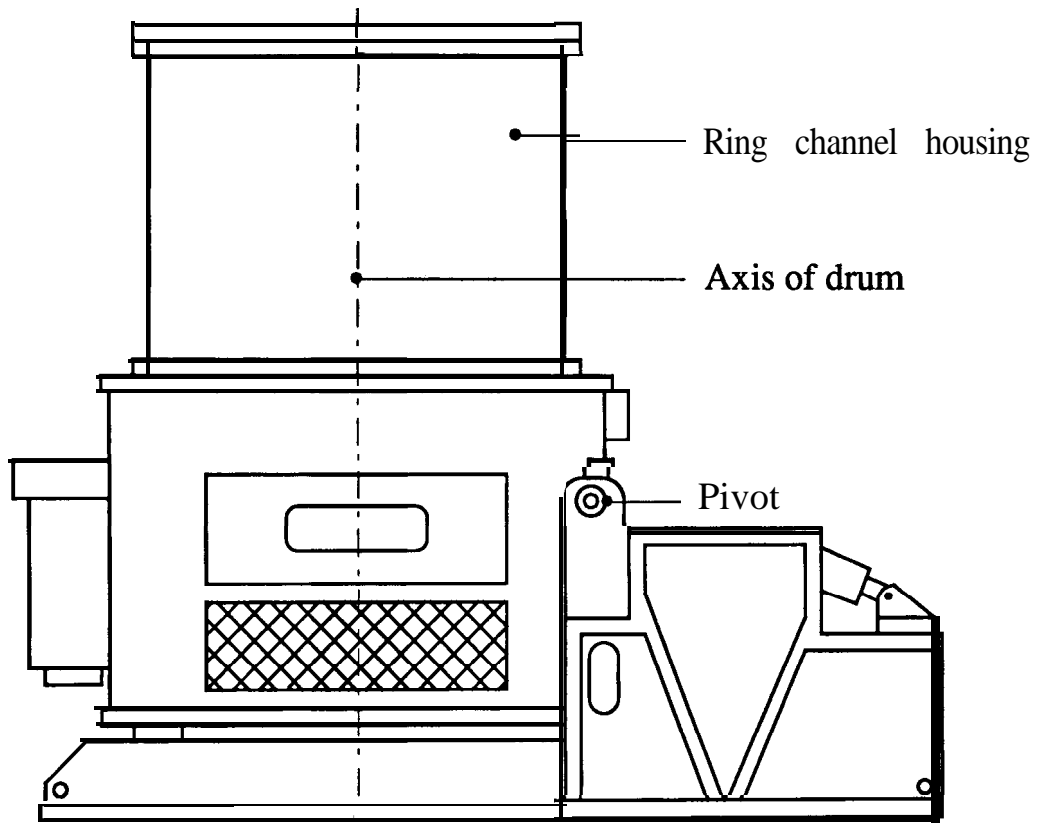


Fig. 1. Elevation of Mark II minidrum centrifuge with drive shaft vertical

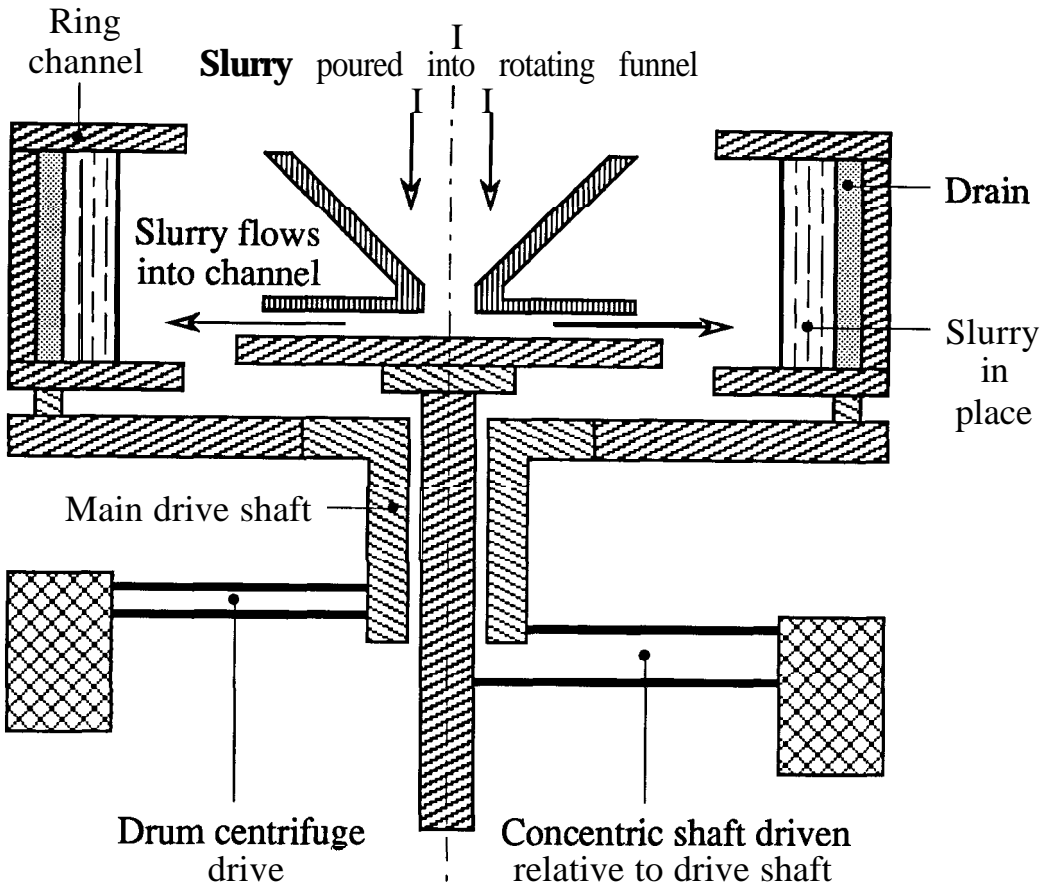


Fig. 2. Section diagram of minidrum showing twin concentric shafts and the slurry spreader in position

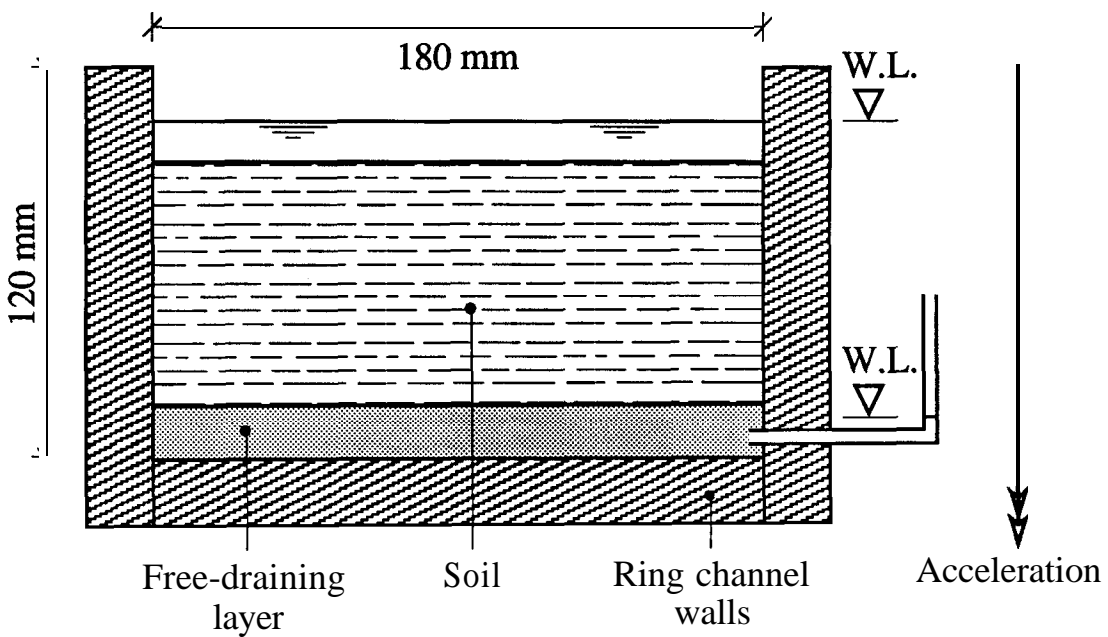


Fig. 3. Minidrum model schematic

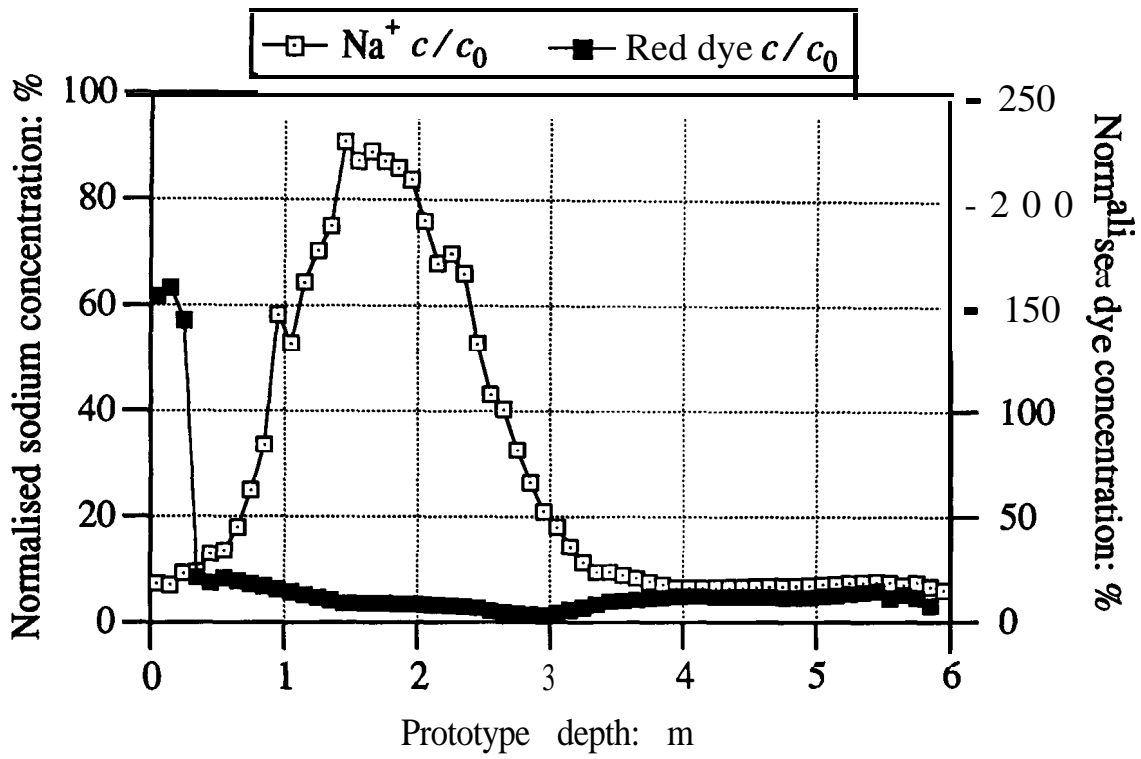


Fig. 4. Contaminant plumes for test BAP1

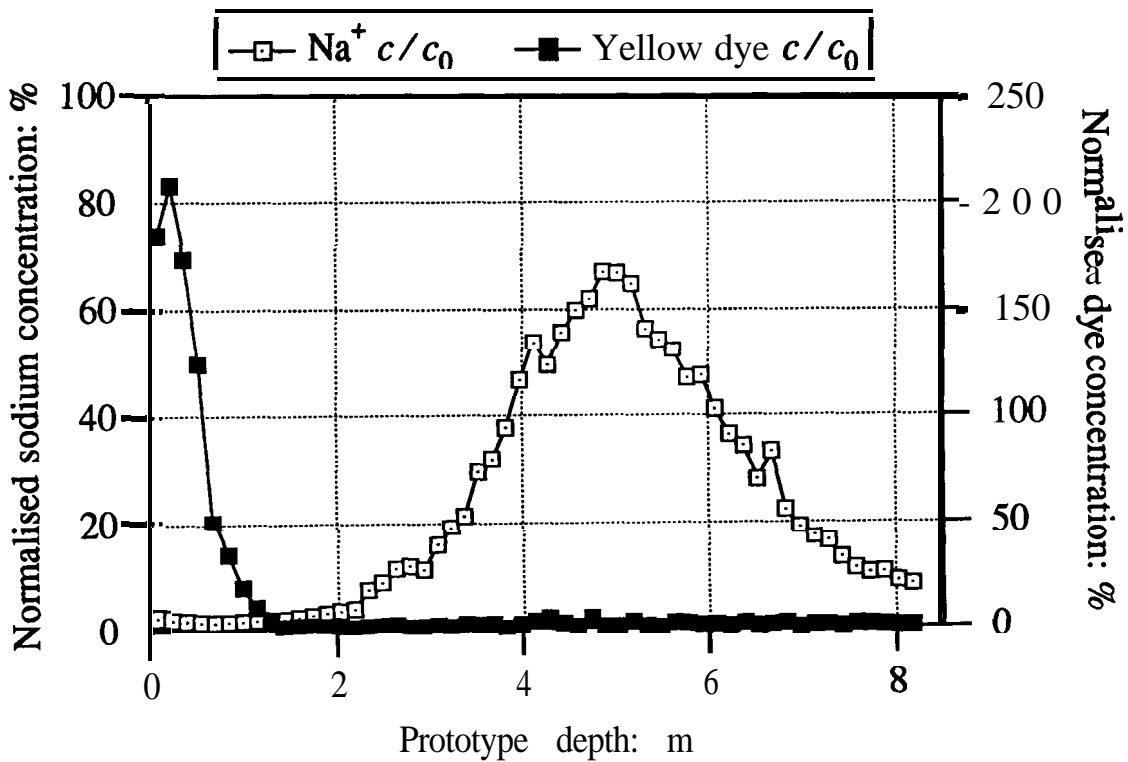


Fig. 5. Contaminant plumes for test BAP2

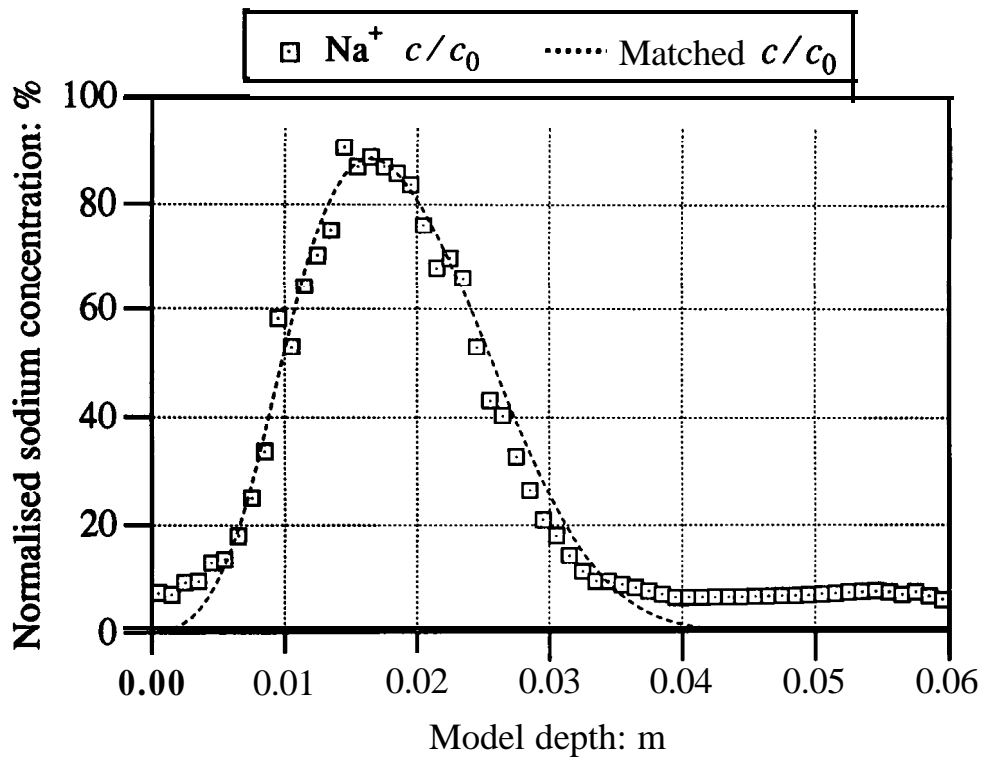


Fig. 6. Sodium plume curve matching for test BAP1

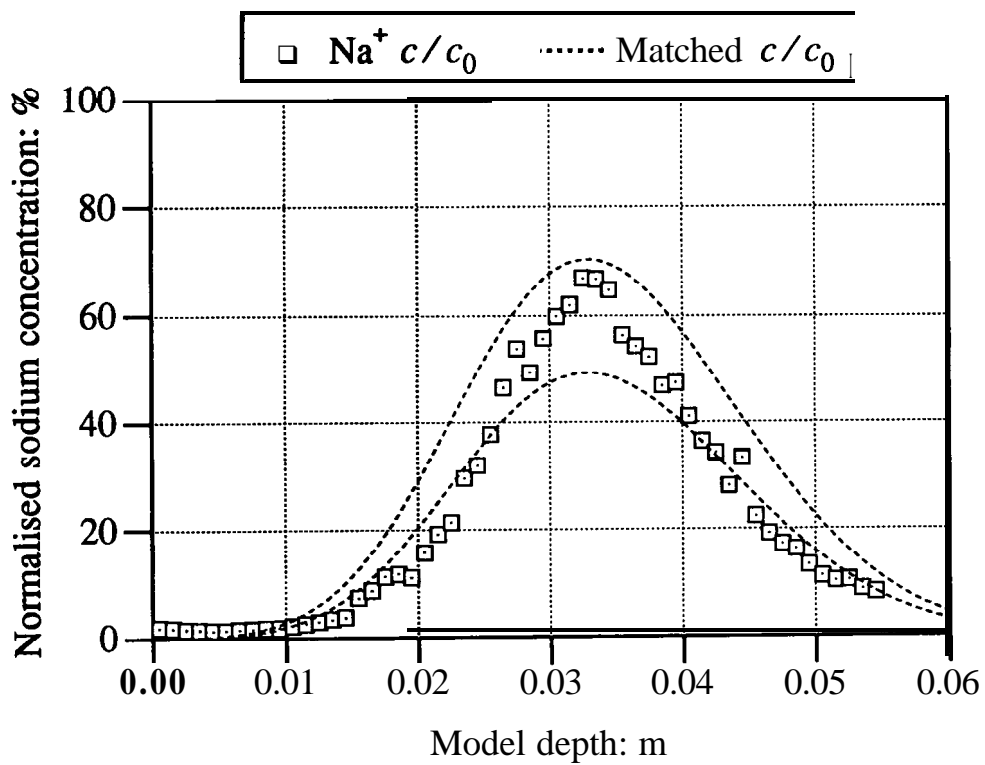


Fig. 7. Sodium plume curve matching for test BAP2