

Pollutant tracking with in-situ fibre-optic photometric sensors in a geotechnical centrifuge

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ABSTRACT: In order to study the migration of contaminants in soils we are currently investigating the use of an *in-situ* fibre-optic photometric sensor to track the movements of a plume of dye tracer. This paper describes the use of these sensors to determine the shape of pollution plumes as they pass through soils in 1-g experiments and also in a high-g centrifuge test. The sensors were buried in a bed of sand with a downward hydraulic gradient across it. A pulse of pollutant was released on to the surface of the sand and the sensors then tracked the progress of the pollution plume through the sand. Preliminary results are discussed, along with details of the sensor and its associated electronics. The development of the sensor design is discussed and their current performance is assessed with a view to future improvements.

1. INTRODUCTION

As with every scientific discipline, theoretical calculations in environmental geotechnics require experimental validation. This is difficult to provide at field scale due to very long time scales and unknown heterogeneity. Laboratory models are called for, at some reduced scale $1/n$. Certain situations, such as the degradation of clay liners by leachate, require the simulation of advection and molecular kinetics through soils whose strength and stiffness is identical to that in the field. The mechanical properties of soils depend on the effective intergranular stresses. Small physical models generally possess small internal stresses. They can however be centrifuged at an appropriate "n-g" gravities to precisely recreate the effective stress and pore water pressure profile encountered in the field. Since pressures are replicated while distances are scaled down, pressure gradients causing flow velocities are enhanced by the scaling factor n . Transport times are accordingly reduced by n^2 . The width of a dispersive plume is reduced by \sqrt{n} rather than by factor n due to the enhancement of dispersivity at high Peclet numbers (Hensley & Randolph 1994).

In the past, pollutants in centrifuge models have been successfully tracked using conductivity measurements (Culligan-Hensley & Savvidou 1994). However for organic pollutants it is more appropriate to use an alternative intrinsic property since electrical conductivity would be relatively insensitive to concentration. In this work, light absorption is used, a property which is easy to measure and which can be

directly related to concentration by Beer's Law (Straughan & Walker 1976):

$$A = \log I_0 / I = k l C \quad (1)$$

where A is the absorbance at a given wavelength, I_0 is the incident light intensity, I is the intensity emerging from the sample, l is the path length, C is the concentration of the light absorbing species and k is a constant, sometimes called the extinction coefficient. Light absorption is the basis of photometry which is used in many chemistry analytical procedures.

2. PHOTOMETRIC DETECTION SYSTEM

In-situ photometric sensors were first investigated for use in soil pollution transport experiments at Cambridge University Engineering Department in 1996 (Treadaway et al. 1997). These photometric sensors successfully tracked plumes of dye passing through a column of sand at 1-g (normal gravity).

2.1 Fibre optic photometric sensor

The devices used in this study for monitoring a dye tracer pollutant are represented in Figure 1. Three different mechanical variations of the sensor are shown. In all of these a 1mm diameter polymer fibre is used to direct light from a light emitting diode (LED) into an optical chamber which is buried in the soil. Pore water passes through this chamber vertically via two polymer filters.

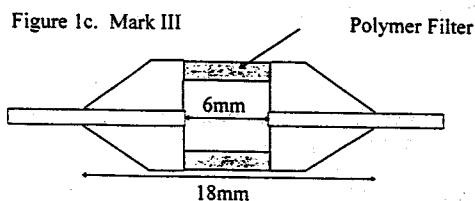
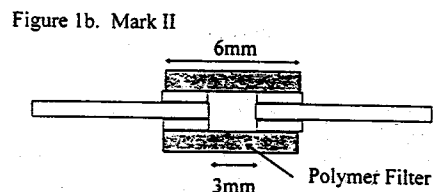
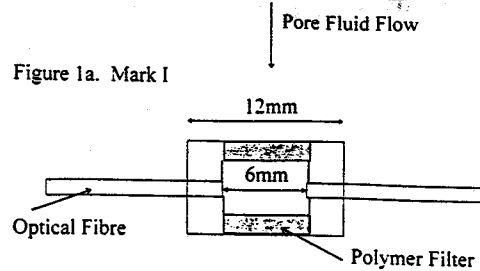


Figure 1. Schematic of photometric sensors.

The sensors shown in Figure 1a, b, c have optical path lengths of 6mm, 3mm and 6mm respectively and are kept free of soil particles by using filters made from polypropylene. Both coarse and fine grades of filter were used with mean pore sizes $91\mu\text{m}$ and $36\mu\text{m}$ respectively. The decision as to which grade to use in any particular test depended on matching the filter permeability to that of the soil. The permeability of the filter should be greater than the soil permeability otherwise the pore fluid is likely to be diverted around the sensor.

The dye tracer in the pore fluid passing through the optical chamber absorbs light, the remaining light exits from the chamber into another, identical, fibre and is taken to a photodiode.

2.2 Light detection electronics

A schematic diagram of the electronics is shown in Figure 2. Light from a 590nm light emitting diode (LED) is collected by a 1mm diameter polymer optical fibre (numerical aperture 0.47) and is transmitted to an optical sensor chamber which is buried in soil. The light which exits the chamber is taken by a similar fibre to a silicon photodiode. The photodiode collects the light and it is then amplified

by a logarithmic amplifier. A log amplifier is used because equation (1) then offers a linear variation of output voltage with concentration of pollutant.

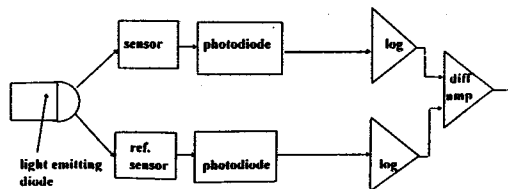


Figure 2. Schematic diagram of electronics.

In order to allow for any variation of LED output, a second, reference channel is incorporated, taking light from the same LED, and passing it to an identical photodiode and log amplifier. The difference between the two channels is then amplified and output.

2.3 Sensor development

The original version of the photometric sensor, the Mark I (Fig. 1a), produced encouraging results tracking pollutant plumes of both dye and copper sulphate at 1-g (Treadaway et al. 1997). The sensors displayed the ability to trace the fate of these coloured contaminants in soil, measured the rate of transport, the concentration and therefore indicated if adsorption had occurred. The coefficients of longitudinal dispersion could then be calculated from the sensor output.

We were concerned however that the sensor diameter of 12mm was rather large for small-scale models in the centrifuge, so a smaller Mark II version was produced which had an external length of 6mm and an optical path length of 3mm (Fig. 1b). Strength was sacrificed for size reduction, the consequence being that the Mark II sensors produced inconsistent results due to flexing of the optical chamber body, which altered the positioning of the two fibres with respect to one another.

These difficulties with the Mark II led to its abandonment and production of the Mark III (Fig. 1c). The Mark III was constructed for strength, it is in essence very similar to the Mark I, the only difference being tapering supports for the optical fibres, which were added to ensure their stability. It is this third version of the photometric sensor that was mainly used in the experiments discussed in this paper.

3. EXPERIMENTAL DETAILS

The response of photometric sensors was measured with increasing concentrations of green food dye

(manufactured by Rayners Essence Group Ltd. (London) initially at 1-g. This was done in two ways: (i) in fluids only, (ii) buried in a bed of fine sand. The bed of sand was located in a soil tank constructed for conducting the one dimensional flow of pollutants. This tank, together with reservoirs for water and dye as well as waste tanks, were built into a steel drum and mounted in the 10m diameter beam geotechnical centrifuge. During centrifuge flight a plume of dye was released and its position tracked with two photometric sensors located at different depths in the sand.

3.1 Experimental arrangement at 1-g

The equipment used for the 1-g tests is shown in Figure 3. The soil sample of 90-150 μm sand (David Ball Co. Ltd. Cambridge) was held in a cylindrical container of 200mm diameter and height 212mm. The sand bed itself had a depth of 130mm and the sensors were buried with their centres at 46mm and 86mm below the bed surface.

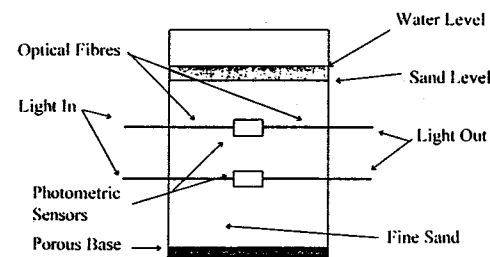


Figure 3. Schematic of the 1-g experimental equipment.

3.2 Experimental arrangement at 50-g

The soil tank and photometric system used in the 1-g tests were incorporated into the geotechnical centrifuge package outlined in Figure 4 below.

The equipment needed to perform, a centrifuge experiment at 50-g, involving the flowing of a dye plume through the soil bed, is far more complicated than that needed to do the same on a laboratory bench. Reservoir tanks were used to store both water and dye, approximately 9 litres of each, and waste tanks were employed to catch these fluids once they had passed through the soil bed. Solenoid valves were used to control flow between the various tanks. A level detector maintained the fluid level at a constant height above the surface of the sand throughout the test. A head device was used to raise the exit water level so that there was only a head difference of 10mm across the soil bed and also to ensure that the water level in the soil tank never dropped below a minimum level, 2mm above the sand surface. Pore pressure transducers (PPT) were

utilised to determine the heights of fluids in the reservoir and waste tanks during the test and a glass manometer, with a camera trained on it, was used to check the fluid level in the soil tank.

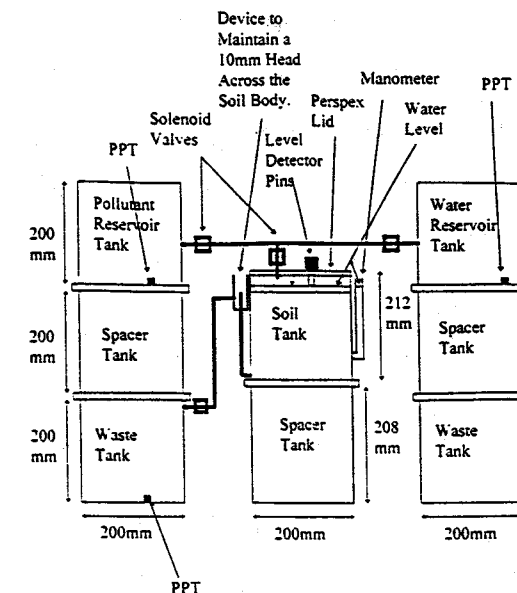


Figure 4. Schematic of the equipment in the geotechnical centrifuge package.

4. RESULTS

4.1 Study of sensor variables at 1-g

In order to fully assess the value of these sensors and determine the conditions under which they function adequately, a large number of bench-top experiments were conducted. These tests consisted of calibrating the sensors, using four different concentrations of dye, under a number of varied conditions.

Initial trials showed that the sensors were sensitive to:

- (i) light infiltration of the porous plastic filter,
- (ii) pore water turbidity obscuring the optical path,
- (iii) air bubble entrapment in the sensor body, and
- (iv) movement of the fibre-optic cables.

Any of these conditions can alter the quantity of light passing out of the optical chamber and hence distort the sensor output.

Modifications were made in an attempt to eliminate these problems:

- (i) for the free solution measurements the tank was covered to exclude external light whilst readings were taken

- (ii) either the nominally 90-150µm sand, sieved to remove particles smaller than 106µm, or coarser 150-300µm sand was used,
- (iii) the sensors and fluids were vacuumed to remove air bubbles, and
- (iv) the sensors were supported to minimise fibre movement.

Further tests were then conducted, these tests attempted to:

- (i) assess the degree of reproducibility (by conducting three calibrations on a pair of parallel Mark III sensors with coarse filters, in fluids only, and compare the results),
- (ii) decide whether the offset of the sensor readings (intercept on the calibration graph) could be zeroed as it is in a UV-VIS spectrophotometer. This was done by artificially altering the intercept and then re-calibrating the sensors to see if the gradient remained the same,
- (iii) compare the Mark I and Mark III sensors (sensor 2 was replaced with a Mark I sensor),
- (iv) compare the effects of the two different grades of polymer filter (sensor 2 was replaced with a fine filtered Mark III), and
- (v) compare calibrations in and out of soil (the two Mark III sensors used in the filter comparison were buried, at the same depth, in 150-300µm sand and then re-calibrated). The results of these tests are summarised in Table 1, and discussed in section 5.1.

Table 1. Results of the sensor variables tests

Type of experiment (Sensor 1 = S1 & Sensor 2 = S2)	Gradient of S1 calibration	Gradient of S2 calibration	Intercept of S1 calibration	Intercept of S2 calibration
(i) Reproducibility check 1	2.723	2.867	6.331	4.150
(i) Reproducibility check 2	2.652	2.817	6.353	4.125
(i) (ii) Reproducibility check 3	2.637	2.824	6.410	4.139
(ii) Intercept changed 1	2.703	2.858	1.368	-1.711
(ii) Intercept changed 2	2.660	2.856	1.821	-2.244
(iii) S1 Mark III, S2 Mark I	2.713	3.341	5.844	5.397
(iii) S1 Mark III, S2 Mark I (2)	2.606	3.245	5.976	5.591
(iv) (v) S1 coarse, S2 fine in dye	2.737	2.901	5.879	3.804
(iv) (v) S1 coarse, S2 fine in sand	2.786	2.947	4.634	4.3862
(iv) (v) S1 coarse, S2 fine in sand (2)	2.792	2.954	4.558	4.345

4.2 Sensor performance at 1-g in fluids only

The response of the photometric sensors to increasing levels of dye concentration is shown in figure 5.

The procedure was to fix the two sensors in place in the empty soil tank. The finer grade of polymer filter was used in these sensors as fine sand was to be used in the proposed centrifuge test. The tank was then filled with de-aired water and put under suction to fill the sensor body with liquid. The tank was covered to exclude light and readings were taken. Next the tank was drained and the sensor bodies emptied using a high pressure jet of air. Dye was added to the water

to a concentration of 0.5%. The solution was then poured back into the tank, vacuum was applied, the tank was covered and then a second set of readings was taken. This process was repeated with 1.0, 1.5, and 2.0% dye solutions to produce the calibration graph seen in Figure 5 below. As expected from Beer's Law the plot shows a high degree of linearity. The linear regression coefficients were 0.9998 for the upper sensor and 0.9959 for the lower sensor.

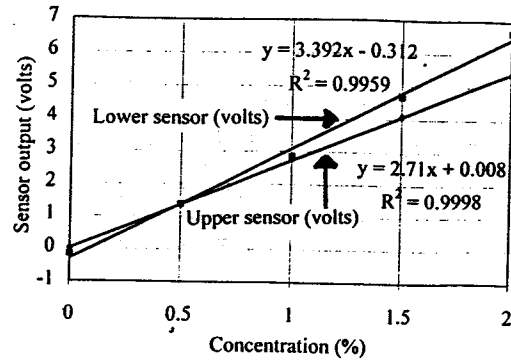


Figure 5. Sensor response to increasing concentrations of dye in water.

4.3 Sensor performance in fine sand

The next stage was to bury the two photometric sensors in the bed of sand described in 3.1 and progressively increase the concentrations of dye flowing through the soil. In order to minimise the mixing of the new concentration with the old, the procedure was to lower the water level to 2 mm above the soil surface before the change of concentration took place. Figure 6 shows the resulting upper sensor stepwise response curve produced from the addition of 0.5, 1.0, and 1.5% dye solutions. Plotting the response against dye

concentration gave a linear relationship with regression coefficients of 0.9998 for both sensors.

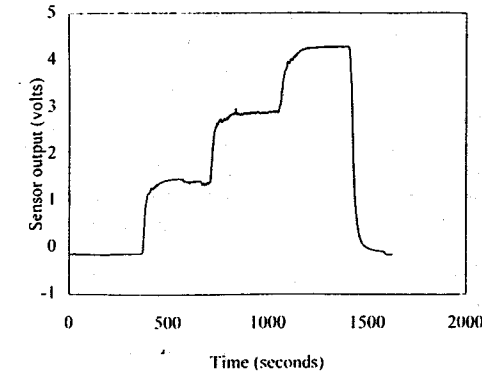


Figure 6. Stepwise curve calibration of the upper sensor whilst buried.

4.4 Tracking of a dye plume at 50-g

The same soil and container used in the 1-g experiments above, together with the ancillary tanks and valves shown in Figure 4, were mounted in the 10m geotechnical centrifuge. The package was taken up to 10-g and then to 50-g. Flow of water through the soil bed under a constant head difference of 10mm, was then initiated. When half of the water stored in the water reservoirs had passed through the soil bed, the water level in the soil tank was allowed to drop to a minimum of 2mm above the surface of the soil. The dye was then added and several litres allowed to flow through the soil bed, driven by the

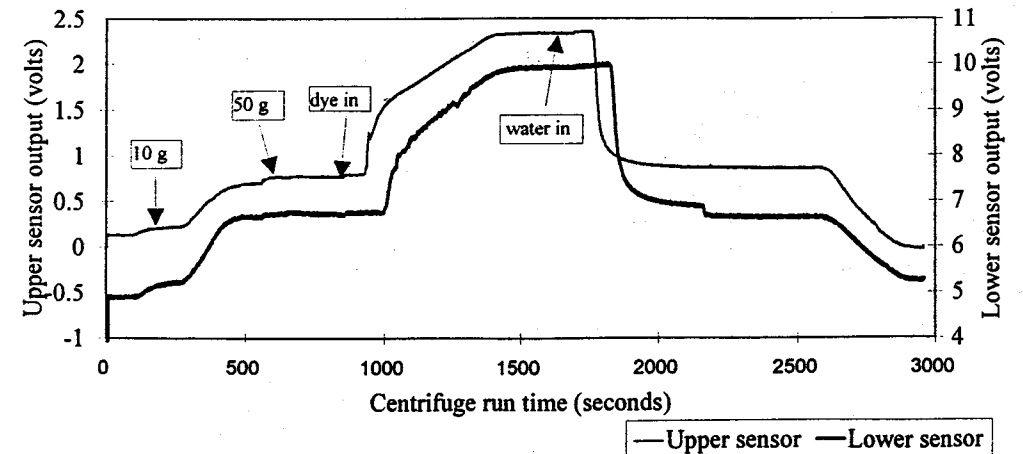


Figure 7. Plume profile recorded at 50-g.

same 10mm head as before. This plume of dye was then washed through with the remaining water from the reservoirs.

The data obtained from the two sensors buried at depths of 46mm and 86mm beneath the sand surface is shown in Figure 7 below.

A comparison of the calibration factors (gradients of calibration graphs) calculated for the same two sensors in free solution and also buried in sand at 1-g and at 50-g is given in Table 2 below.

Table 2. Calibration factors (gradients) for the two sensors

Type of experiment	Gradient of calibration	
	Upper sensor	Lower sensor
Free solution at 1-g	2.710	3.392
In sand at 1-g	2.749	3.622
In sand at 50-g	3.1*	6.2*

*From Figure 7.

5 DISCUSSION

5.1 Sensor variable study

In the improved environment described in 4.1 the results in Table 1 were produced and from these the following observations were made:

- (i) the degree of reproducibility of sensitivity was within 4%,
- (ii) the intercept of the calibration is merely an offset which can be zeroed, as in the auto-zero facility of a

UV-VIS spectrophotometers and that only the calibration gradient (calibration factor) is important, (iii) the Mark I and Mark III sensors have a similar

degree of reproducibility and the Mark I sensor had a tendency to be about 20% more sensitive, (iv) the grade of the porous plastic filter used has no effect on the sensitivity, however the finer grade may delay reaction time (this delay is negligible if the permeability of the filter is greater than the permeability of the soil), and (v) reproducibility between calibrations conducted in and out of soil is similar to that between calibrations conducted under the same conditions, e.g. less than 4%.

5.2 Effect of gravity on sensors

It is apparent from Figure 7 that there is a significant effect of gravity on the signal from the photometric sensors. It is possible to distinguish two plateaux from the sensor output when the centrifuge is running steadily at 10-g and then at 50-g. The sensitivity at high-g also changes (Table 2). The reason for this high-g effect is not clear. Various possibilities exist, for example it is possible that the plastic filters could bend under the influence of the increased soil and water pressure, and reduce the light intensity passing through the sensor. However, the plastic is white and might be expected to increase the light level by reflection, not decrease the light level as observed. Increased voltage signifies increased concentration and hence decreased light intensity.

Another possibility is that small bubbles exist inside the sensors, despite every effort being taken to avoid this eventuality, but the increased pressure should again decrease the size of the bubbles and so the light level should increase, not decrease, as observed.

It is possible that there was a g-effect on the reference sensors, identical sensors which were tied in light-tight wrapping to the outside of one of the reservoir tanks, but again the direction of the observed effect is such that the movement due to g would have to increase the light transmission of the reference sensors which seems implausible.

A plausible explanation is that the g-effect on the optical fibres themselves was the cause of this reaction. The inexpensive fibres used have a minimum radius of curvature of 100mm, a radius less than this will effect the quantity of light passing down the fibre. It is possible that the reference fibres were more securely fixed than the test fibres, so that preferential bending could lead to unwanted attenuation. Work is continuing on this topic.

5.3 Sensor reaction to plume of dye

Both sensors respond to the pulse of pollutant, and they respond in the same way although to a different degree. Their output can be used in a variety of ways.

As expected, the lower sensor responds later than the upper sensor, providing an in-situ measurement of flow velocity which should correlate with values of

permeability, porosity and observed hydraulic gradient.

Each sensor displays the shape of the passing plume. The lack of sharpness of the front of the pollution plume compared with the back, observed with both sensors in Figure 7, may have been due to differences in the switching over of dye to water compared with water to dye.

It may be noted that the trailing slope shows more dispersion at the lower sensor than at the upper. This is as expected considering the fact that there is 40mm of sand between the two sensors which causes extra dispersion.

In principle, such signals can also be used to measure the dispersion coefficient (Treadaway et al. 1997).

Realistic predictions of concentration can be made for experiments at 1-g using the calibration factors in Table 2 above. However this is not true at high-g and further work is necessary to understand and reduce the g-effect on the sensors. To be able to measure concentration profiles and the effect of the adsorption of pollutants on soils in geotechnical centrifuge experiments it is necessary to either reduce the sensitivity of the sensors to high-g or to run a stepwise calibration during the centrifuge run.

Buried sensors will be invaluable in establishing imposed transients in contaminant boundary conditions.

5.4 Possible sensor modifications

Possible modifications to reduce g effect:

- (i) replace the polymer filter with a brass filter which would not deflect under pressure,
- (ii) use an alternative, high quality, optical-fibre which has a small bend radius (down to 2mm),
- (iii) support optical-fibres more rigidly, and
- (iv) route the reference and samples cables more closely.

6 CONCLUSIONS

In-situ sensors can be used for tracking coloured pollutants in both 1-g and centrifuge tests supplying information on: contaminant boundary conditions, advection rates, plume widths, dispersion coefficients and, ultimately, sorption. However, this technology requires further development before the sensors can be relied upon to give absolute measurements of concentration at high-g. Modifications or procedures are required to eliminate difficulties due to: turbidity, air infiltration, cable movement and g-effect. Work will continue both at Cambridge and at LNEC Lisbon.

These in-situ probes should eventually be useful in geotechnical centrifuge model tests on relatively impermeable materials, such as clay barriers, for

predicting arrival times and concentration levels of pollutants as chemical reactions take place in the soil.

7 ACKNOWLEDGEMENTS

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