Measurement of side-wall leakage in soil columns using fibre-optics sensing.

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Abstract: Side-wall leakage - the preferential flow of water or pollutants near the wall of a soil containment vessel - has been studied using in-situ fibre-optical detection of a dye solution at the boundary and in the centre of a soil column. A difference in flow velocity was clearly observed between centre and column wall boundary for different surfaces. The boundary effect was nullified or reversed by modification of the wall surface.

Introduction

Laboratory experiments for investigating the permeability of soils or contaminant tranport often involve the study of a flow of water through soil columns held in tubes of steel, glass or other rigid material. There is often thought to be a boundary effect or side wall leakage associated with such columns, i.e. the local permeability of the soil at the interface with the tube is greater than the permeability at the centre of the column. Flexible walled permeameters have been used to overcome such effects (e.g. Daniel, Anderson and Boynton, 1985).

Nevertheless because of their simplicity, many experiments on permeability or contaminant transport are carried out in rigid tubes. Schofield and Poorooshasb (1988), studied the density driven flow of salt contaminant in a rigid walled column of silt at increased gravity in a centrifuge. They found evidence of fingering (increased flow) near the wall when the contaminant was moving down through unsaturated soil. In studies of contaminant transport of NAPLs (non-aqueous pollutant liquids), fingering has been reduced near the window of a centrifuge soil sample by sand blasting of the glass (Taylor 2000). Budhu (1991) has compared results of organic permeation in rigid walled and flexible walled permeameters. In most cases, soil permeability ratios of organic / water were greater for the rigid wall permeameter, suggesting side wall leakage effects. In a study of the flow of water through plate-like wood chips, as used in paper pulp-making, evidence of a wall-effect was found (Comiti and Renaud, 1989). They proposed two reasons: a change in the viscous resistance, due to a difference in the surface roughness between the wall and a particle, and also a reduction in tortuosity near the wall.

In this laboratory we are currently studying the transport of water-soluble contaminants through soils and simulated landfill liners using fibre-optic sensors. We have used these sensors to track the movement both of a dye tracer and of copper salt in 1-dimensional experiments (Treadaway, Lynch and Bolton, 1997,1998). We also have applied this technology to contaminant transport studies in geotechnical centrifuge experiments (Treadaway, Lynch and Bolton,1998). Using similar technology it was decided to measure the boundary effect by measuring the time differences at which a plume of water-soluble dye passes sensors at the wall and at the centre of a column of soil.

Experimental procedure

The experimental apparatus is shown in Fig. 1. The soil sample is contained in a rigid Perspex tube, 120 mm outer diameter and 200 mm deep. Below the soil is a 20 mm layer of gravel retained by porous plastic sheet. The surface of the soil is covered by another sheet of porous plastic. This avoids disturbance of the surface by the incoming stream of water. Apart from the time of the plume injection, the water level is maintained constant 1 cm above the soil by means of an electronically operated solenoid valve, controlled by the dry / wet resistance of two stainless steel pins. The outlet of the soil container is to a tap of adjustable height, to provide a range of hydraulic gradients.

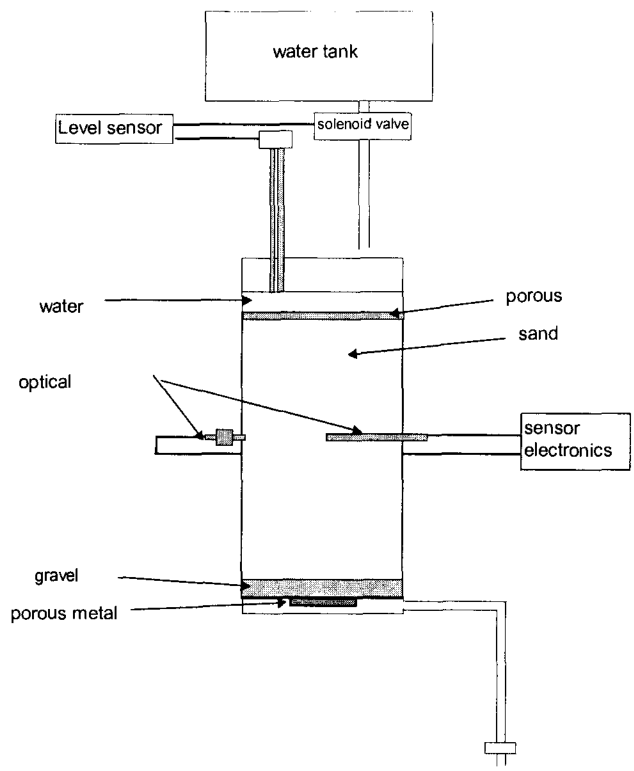


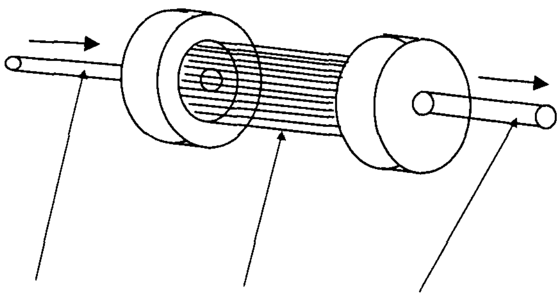
Fig.1. Experimental arrangement

<u>*Preparation of the fully saturated soil sample*</u>

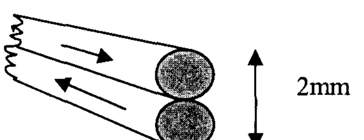
The tube is filled with de-aired water and sand of particle size 300-600 mm (fraction C) or 600-1200 mm (fraction B), (David Ball &Co., Lolworth, Cambs). Sand is introduced into the water by keeping it fully saturated from a bucket containing soil and de-aired water. A 3 mm thickness piece of porous plastic is de-aired in water and then covers the sand. This procedure is more accurate than using filter paper, which does not prevent water flow soil disturbance. After the sample is loaded, the model is consolidated using a shaking table.

<u>*Injection of the plume*</u>

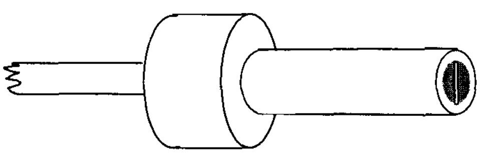
The dye is prepared by diluting the concentrate, (Raynor's Green food colouring, Middlesex), to 1% by volume. At first, steady state conditions are established in the column, with a constant head of water. When flat baseline conditions are observed from the sensors the plume injection is carried out in the following manner: The water level is allowed to fall until the soil surface is almost exposed. 60 ml of green dye solution is poured evenly into the water above the porous plastic, and allowed to pass into the soil. When the dye has almost completely entered the soil, water flow is resumed and controlled at a constant head by means of the water level controller which operates the water tank solenoid valve, and keeps the hydraulic gradient constant.



(a) Transmitted light probe (Mark 4 type)



(b) Reflected light probe. Type "bi-fiber"



(c) Fibre-optic reflected light probe. Type "rfp"

Fig 2 . Fibre-optic photometric sensors,

<u>Sensors</u>
Three types of photometric optical fibre sensor have been used in this work:

1. A light-transmission type described previously, (Treadaway, Lynch and Bolton, 1997), shown in Fig. 2(a), in which light from a light emitting diode passes through the pore fluid; the transmitted light is measured by a photodiode circuit.
2. Two light-reflection types are also shown in Fig. 2(b, c). In these sensors the light from a light emitting diode is transmitted by a fibre to the soil sample. It passes through the voids, is reflected from the soil surfaces,and collected by another fibre. Optionally a layer of geotextile mesh can be used to increase the void space. This has the effect of increasing substantially the sensitivity but at the penalty of increasing the response time, since there will be a time associated with this mesh chamber filling and emptying of dye. In these experiments no mesh chamber was used. The fibres used in the transmission type are standard step-index fibre of 1mm core diameter and 2.2mm outer diameter. In the "bi-fibre" type, the plastic cladding was stripped from two 1mm fibres and the two cores glued together so that the fibres were parallel and the ends level. A thin shrink-wrap sleeving was applied to the fibres. This small, un-intrusive sensor can be applied with minimal disturbance to the soil.

<u>Electronics:</u>
The two sensors are connected to an electronic circuit which provides the following functions:

1. Light emitting diodes and associated power supplies;
2. Photodiodes for measuring in-coming light intensity;
3. Logging amplifiers which allow the output voltage to vary linearly with dye concentration, according to Beer's Law (light absorbance is proportional to dye concentration),
4. A differential amplifier which compares the light intensity changes in sample and reference sensors.

The output signals are stored in a data logger (Handyscope) connected to a personal computer. Details of the electronics system have been described previously (Treadaway, Lynch and Bolton, 1997,1998).

Results and Discussion:

<u>Sensor calibration</u>
Fig. 3 shows the calibration plot for the two sensors, i.e. the output voltage at various

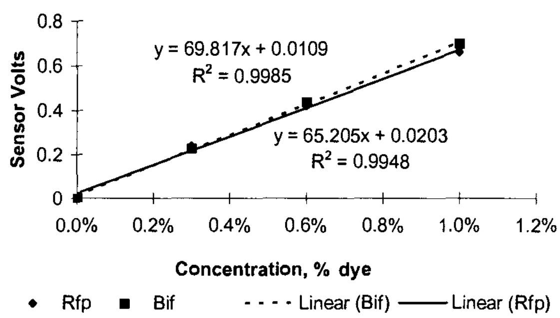


Fig. 3(a) Sensor calibration plot in Soil B.

concentrations of dye. The packing of the soil granules around these reflective probes could affect the calibration, so both soil types were used. In fact, the slopes of the linear regression fit did not vary significantly. It is recognised that a potential problem with this method of calibration is that there may be adsorption of the dye on to the soil particles surfaces, so that the concentration sensed by the fibre is reduced. However in this case there appears to be little adsorption of the dye by the sand, and the linear nature of the calibration plots agrees with Beer's Law.

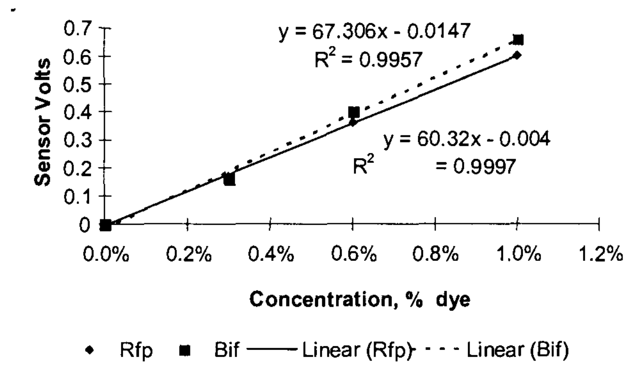


Fig. 3(b). Sensor calibration plot in soil C

<u>*Rigid, uncoated column walls*</u>

Fig 4 shows the plumes detected by two sensors of the reflective type, mounted at the edge and at the centre of a column of Fraction B sand (0.6-1.2mm particle size range).

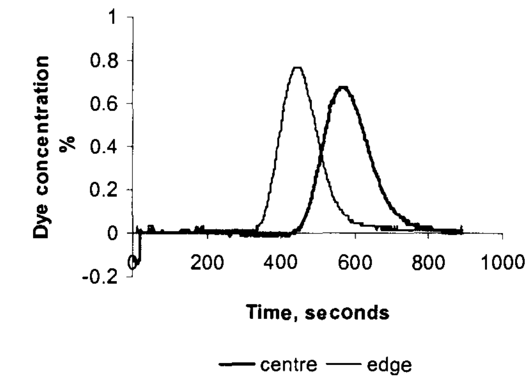


Fig.4 Plume at centre and wall of column (sand B, uncoated wall, 0.77 hydraulic gradient).

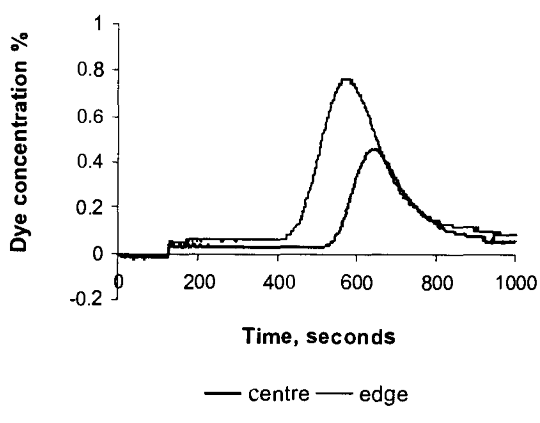


Fig.5. Plume at centre and wall of column (sand C, uncoated wall, 0.77 hydraulic gradient).

The sensor at the edge was mounted with the sensitive surface mounted flush with the column wall. Fig. 5 shows similar plumes in Soil C 9 (300-600 μm particule diameter)

It is clear that in both cases the plume at the edge leads that at the centre. In Soil B the difference is about 50% of the plume width and in soil C, 26% of the plume width.

<u>*Modified column walls*</u>

The column wall was then coated with double-sided adhesive tape and coated with the same sand on test. In this series the plume of dye at the edge is now retarded by the effect. Fig. 6 and 7 show the results collected at the same hydraulic gradient as Figs. 4 and 5 above but with coated walls.

The plume at the edge now can be seen to coincide (Fig. 6.)or even to trail behind (Fig. 7) that of the centre, in contrast to the uncoated wall results. This seems entirely reasonable since the sand-coating of the walls has reduced the relative disturbance to the packing at the edge, and therefore the local increase in voids ratio. An alternative explanation is perhaps that there is now an affinity between the dye and column surface.

Figs 4-7 were all obtained at a constant hydraulic gradient of 0.77. These simple experiments suggest that the boundary effect is increased with larger soil particle sizes. This is difficult to explain since the suggested mechanism is dependent on packing geometry rather than grain size.

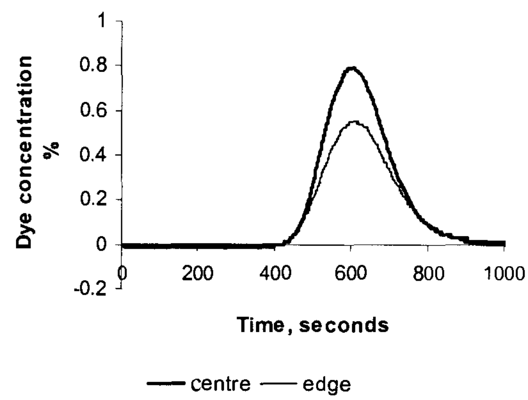


Fig.6. Plume at centre and wall of column (sand B, 0.77 hydraulic gradient, coated wall).

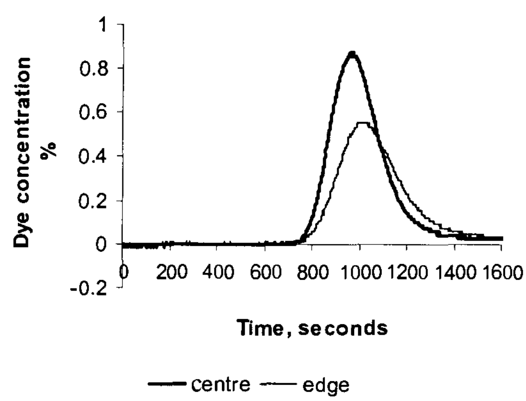
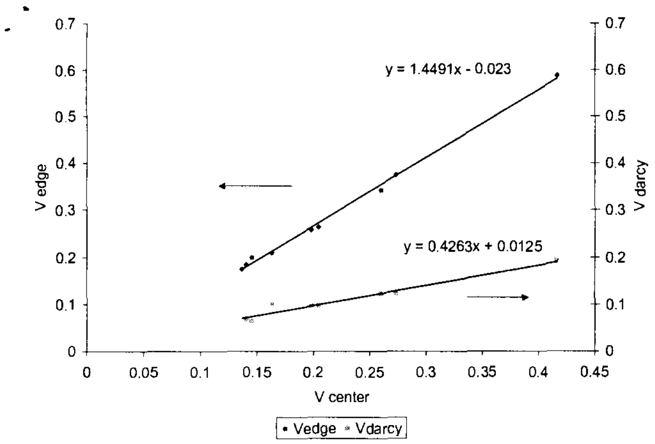


Fig.7. Plume at centre and wall of column (sand C, 0.77 hydraulic gradient, coated wall).

It shows that the delay is more exaggerated at small hydraulic gradients.



Fi. 8 Velocity at the edge vs. velocity at the center; Soil B

In Fig.8, the velocity at the edge measured by the edge-mounted sensor, is plotted against the velocity at the centre for different hydraulic gradients, for Soil B,uncoated column. Also shown is the Darcy velocity V_d, calculated from the flow rate measured at the column exit.

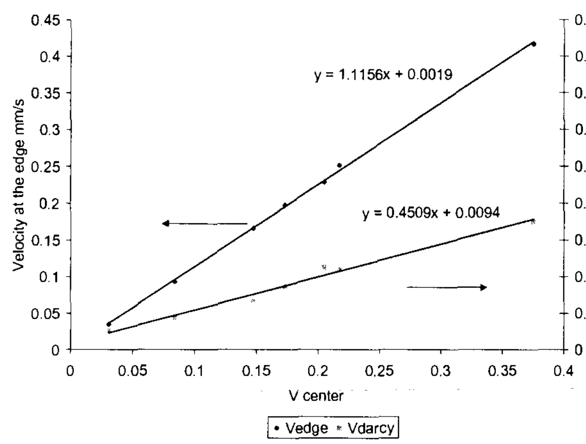


Fig 9 Ratio Vedge/Vcenter, Soil C

v_{edge} , measured by the edge-mounted photometric sensor. These velocities were calculated from the times taken for the dye to pass through 90mm depth of soil. The ratio of v_d to v_{centre} is an estimate of the porosity, n. Fig. 9 accordingly gives a porosity value for soil B of 0.44 This compares to a value of n = 0.40 (for both soils B and C) obtained by dry density measurement. Similarly for soil C, the estimated porosity from the ratio of v_d to v_{centre}, shown in Fig. 10, is 0.45.

In both soils. the ratio of the slopes v_{edge}/v_{center} is greater than 1.

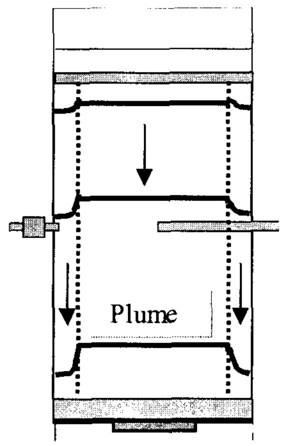


Fig. 10 Plume shape in sand fraction C

The permeability is related to the porosity by the Kozeny-Carmen equation (Bear,1972).

$$K = \frac{pg}{\mu}\left[\frac{n^3}{(1-n)^2}\right]\left(\frac{d_m^2}{180}\right)$$

Assuming that the porosity n varies from n_c at the center to n_e at the edge and d represents the grain size, from this equation, in terms of void ratio e, K/n is proportional to e^2

As $V_{edge} = (k_e/n_e)\ i_{edge}$
$V_{center} = (k_c/n_c)\ i_{center}$
And $i_{edge} = i_{center}$ $\Rightarrow$ $V_{edge} / V_{center} = (e_{edge}/e_{center})^2$

From Fig.8 and Fig9 we know that the edge to center velocity ratio for Soil B is 1.45 and 1.11 for soil C, so e_{edge}/e_{center} is respectively 1.2 and 1.05 which confirms the difference in packing arrangement between these soils.

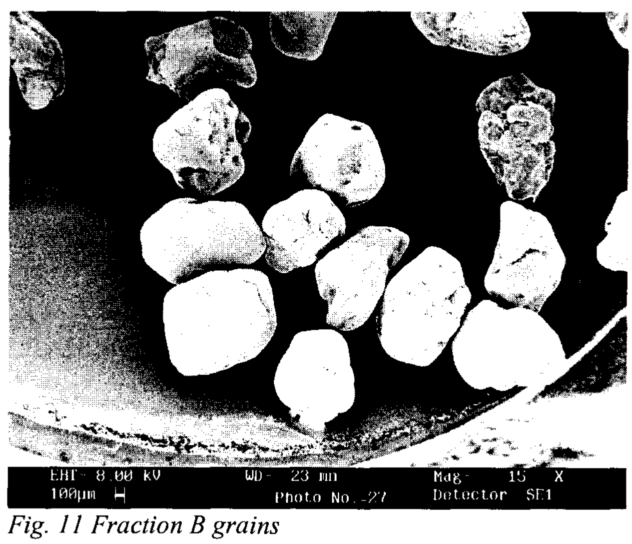


Fig. 11 Fraction B grains

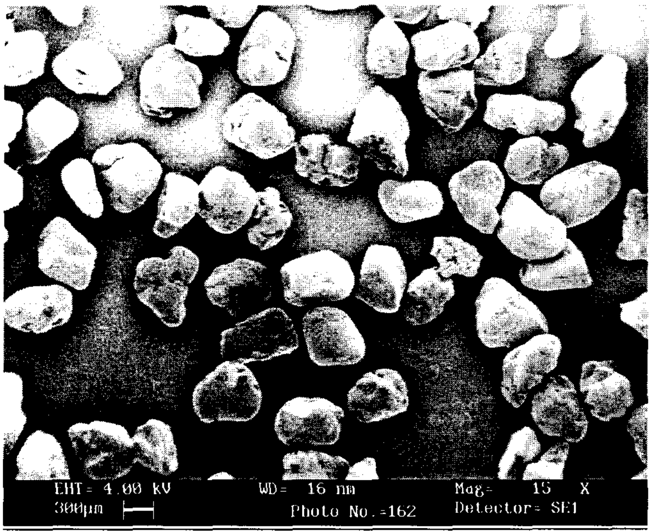


Fig. 12 Fraction C grains

A theory for boundary effects considering regular packings of uniform sized particles has already been investigated by bobby Hardin (BA.Hardin, 1989). He defined an equivalent side length in order to apply his theory to volumes with boundaries of arbitrary shape. Tests indicate that the theory works for angular particles and for graded materials providing particle size is represented by the size for which 10% of the particles (by mass) are finer. In Figure 11 and 12 it is possible to make out the triangular shape often observed in both soils. This feature implies also a different arrangement at the edge of the perpex tube.

<u>Results with transmission- type sensor</u>

In another series of Soil B experiments, the transmission sensor (Mark 4) was periodically moved across the diameter of the column, to measure the difference in plume delay. Again, in clean unmodified columns the plume travelled faster near the wall. See Fig. 11. The sensor at the edge was the reflective probe.

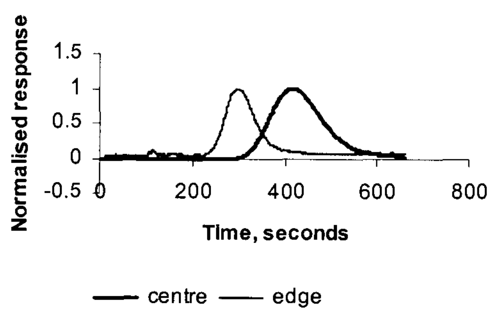


Fig. 13(a) Sensors at centre and edge of column.

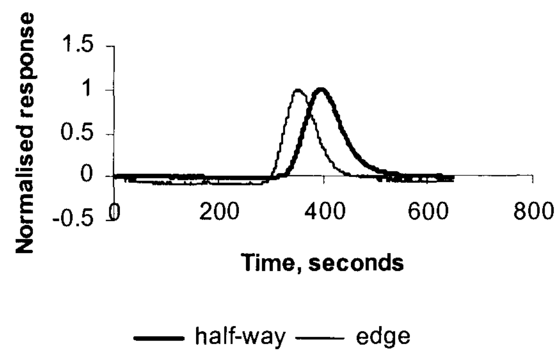


Fig. 13(b) Sensors at edge and mid-way between centre and edge.

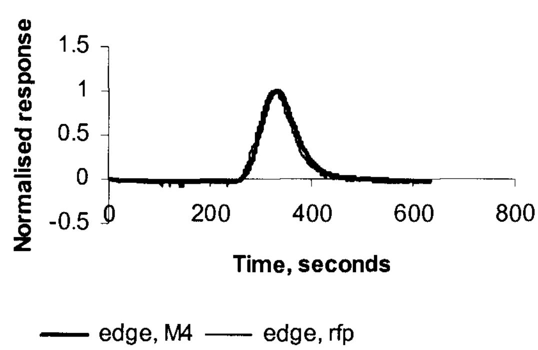


Fig. 13(c) Both sensors at edge of column.

The time delay between the arrival of the plume peak concentration in the measurements above was: Fig. 13(a) 119 seconds, Fig 13(b) 46 seconds, and Fig. 13(c) 4 seconds, respectively. These results agree with those of the uncoated column above, in that the edge plume leads the centre plume for uncoated walls. The plume shape as well as the time of arrival is identical for the two different sensors, when both are mounted at the edge of the column.

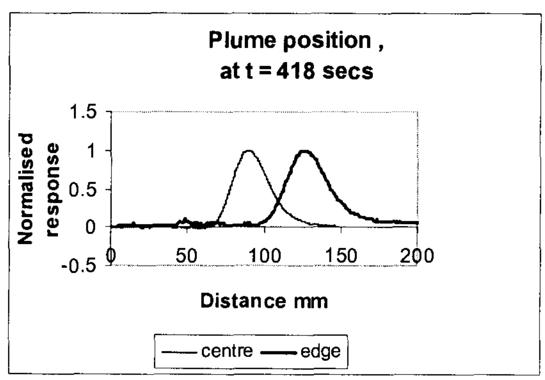


Fig. 14. Plume shape at the sensor position, 90 mm from top, at t = 418 seconds

Conclusions

In-situ fibre-optic sensors have been used successfully to measure the time difference of plume arrival at the edge and in the centre of a soil column. As expected, these results show evidence for the permeability boundary effect, the plume of dye moving faster at the soil column wall boundary.

When the inside wall of the soil container was roughened by coating with sand, the previously seen effect can be nullified or even reversed.
The void ratios at the edge were 50% and 20% larger than those at the column center, for the two sand investigated.

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