

CSIRO
AUSTRALIA

**A LABORATORY STUDY OF THE FLOW
PROCESSES THROUGH LAYERED
PROFILES IN RELATION TO CLOGGING
IN ARTIFICIAL RECHARGE BASINS**

By P. Pavelic and C.D. Johnston

TECHNICAL MEMORANDUM 93/2
January 1993

Division of Water Resources

**A LABORATORY STUDY OF THE FLOW PROCESSES
THROUGH LAYERED PROFILES IN RELATION TO
CLOGGING IN ARTIFICIAL RECHARGE BASINS**

By P. Pavelic and C.D. Johnston

Division of Water Resources, Perth Laboratory

Technical Memorandum 93/2

January 1993

CSIRO

Institute of Natural Resources and Environment

Division of Water Resources

ISBN 0 643 05373 5

Publications enquiries to:

**Divisional Editor
CSIRO Division of Water Resources
GPO Box 1666
Canberra ACT 2601 Australia
ph. (06) 246 5717
fax (06) 246 5800**

ABSTRACT

Laboratory column experiments were performed to study the flow processes which occur in artificial recharge basins where clogging causes a low permeability layer to develop on top of higher permeability materials. In the laboratory experiments, a fine textured layer (sandy loam) was placed on top of a coarse sand to simulate a crust or clogging layer which develops in artificial recharge basins. The primary objective was to demonstrate that desaturation of the coarse materials below the fine textured layer would cause a dramatic reduction in flux rates. Numerical simulations had shown that flux rates are sensitive to the unsaturated hydraulic properties of the coarse materials but may also be dependent on whether the (fine textured) clogging layer itself desaturated.

Experiments were conducted to produce different pressure heads in the coarse materials under the fine textured layer. Two different sets of experiments compared behaviour where the materials were able to desaturate by allowing air access to the column and behaviour where air was excluded from the column.

Results showed that flow rates were reduced dramatically when the pressure head in the coarse materials fell below their air entry value and the materials desaturated. Where air was prevented from entering the column, pressure head fell below the air entry value without affecting the hydraulic conductivity of the materials or the column as a whole. Apparent difficulties with the stability of the fine textured layer and tensiometer emplacement prevented conclusions to be drawn about any possible desaturation in the fine textured layer and its effect on flow rates.

The experiments have shown that hydraulic processes within the subsoil below the crust or clogging layer may dominate flow rates through the profile. Development of unsaturated conditions should be avoided to maximise flow rates. Also, the unsaturated hydraulic characteristics of the materials below a crust or finer textured layer are important to the operation of a recharge basin.

1. INTRODUCTION

1.1 Artificial Groundwater Recharge

Artificial groundwater recharge is the process of enhancing the recharge of surface waters to groundwater aquifers. This is generally achieved by using structures which include infiltration basins or injection wells, with the choice of facility generally dependent on local hydrogeology. Artificial recharge is conducted for several reasons; disposal of excess surface water, increasing water levels to prevent movement of poorer quality water into aquifers, disposal of polluted water and storage of water in aquifers for future use.

Artificial recharge for storage of water in aquifers has several distinct advantages over surface water storage including the absence of water loss by evaporation, uniformity in quality of the recovered water and potential savings in land (Behnke, 1969).

The ever increasing demand on groundwater in Australia has resulted in greater interest in artificial recharge. Until recently, Australia's involvement in artificial recharge has been almost totally confined to the Burdekin Delta region of northern Queensland where around $100 \times 10^6 \text{ m}^3$ of river water is recharged annually to supply irrigation requirements for the local sugar cane industry (O'Shea 1967, Hazel and Hillier 1989). Artificial recharge has also been used in the Lockyer and Callide valleys in Queensland (Hazel and Hillier 1989) and on the Fortescue River in Western Australia (Clark and Kneeshaw 1983). More recently, pilot recharge studies have been reported at Boundary Creek near Geelong (Johnston 1990).

The recharging water is usually turbid (containing clay to silt sized particles) to some degree and may contain nutrient loads sufficient to sustain biological activity. In such cases clogging will develop with an associated decline in the rate of flow with time resulting in reduced accessions to the groundwater system.

1.2 Clogging Mechanisms

The development of clogging is a complex process which results from the interaction between the recharging water and the material within it and the basin soil. Clogging

mechanisms include the settlement and filtering of suspended matter in the recharging water, biological activity and chemical interactions, although clogging is not necessarily restricted to any one mechanism. The formation of a clogging layer of greater hydraulic impedance is generally characterised by lower saturated hydraulic conductivities, greater density and finer pores than the hydraulically undisturbed underlying soil. Such characteristics have led to the use of such terms as seals, crusts and linings to describe clogging. Clogging is generally confined to the soil surface with its effect diminishing with depth. The depth of clogging (or more accurately the zone of increased impedance) is generally found to occur at or near the surface for soils of sand texture or finer (Schuh and Shaver 1989). Behnke (1969) concluded that clogging was a surface sealing process from pressure distributions during a laboratory study. Flow rates were observed to decrease significantly at a critical period when a complete layer forms with further sedimentation thickening this layer. Clogging has been found to increase the hydraulic impedance of the soil up to 2 or 3 orders of magnitude, with depths generally ranging to several centimeters (eg. Shainberg and Singer 1986, Schuh and Shaver 1989, Johnston, 1990).

Studies to date have been focussed on clogging by suspended matter (eg. Berende 1967, Behnke 1969, Schuh 1988). Clogging by suspended matter may occur by two means, namely gravitational settling and interstitial settling (filtering). Filtering has been found to be the more effective in sealing the basin bottom. Previous studies have shown that the degree of clogging and associated depth of penetration of suspended matter to be dependent on the ratio of pore size of the soil to the sediment size of the recharging water.

Sedimentary clogging has been reported to occur at concentrations as low as 50 mg L^{-1} (Behnke 1969).

Biological clogging may be caused by microbial growth within the soil or by filtered out layers of organisms suspended in the water (often referred to as a filter cake). Biological clogging is usually confined to nutrient rich waters of low turbidity and sufficiently warm water temperatures. Chemical factors usually play a minor role in clogging provided chemical variations between the recharging water and the interstitial water or soil matrix. Chemical clogging may result by the formation of a precipitate or by the dispersion of clay found naturally within the soil.

2. BACKGROUND AND AIMS OF THE STUDY

An intensive pilot scale artificial recharge basin study at Boundary Creek (Johnston 1990) was conducted as a preliminary trial into the feasibility of supplying groundwater for the city of Geelong by recharging local creek water to the Barwon Downs aquifer. The hydrological conditions which prevailed at the artificial recharge site resulted in the dominant control on flow out of the basin to be a finer textured layer, (notably a fine sandy loam) at depth. Installation of a "slot" of coarse textured soil through the limiting layer significantly boosted flow rates however significant clogging eventually lead to a dramatic drop in infiltration rates (Johnston 1993). Clogging was found to be due to the accumulation of suspended sediment and the growth of algae. The resulting impeding layer was observed to consist of a very thin sediment layer and surficial algal mat. The clogging process will be a major economic consideration in recharge basin management.

A numerical approach by Johnston (1990) has shown that a dramatic reduction in infiltration rates occurs upon desaturation of the bottom of the clogged basin lining. The numerical model showed that the reduction in infiltration rate is extremely sensitive to the value of hydraulic conductivity of the elements within and below the lining. The reduced infiltration is therefore very sensitive to exactly where the unsaturated conditions develop (either within the clogging layer itself and/or the materials below) and the dependence of hydraulic conductivity on the degree of unsaturation. The objective of this work was therefore to simulate the clogging process in a laboratory experiment and examine the development of an unsaturated zone below a clogging layer.

With this objective in mind, a laboratory column study was devised and conducted to determine the hydraulic processes which result from clogging under steady state flow conditions. This was achieved by applying a relatively thin layer of low permeability soil above a coarse textured layer of higher permeability. Particular attention was paid to the formation of negative pressure beneath the finer textured layer and conditions which determined whether the low permeability layer and underlying soil remain saturated. The variability of hydraulic conductivity within and below the low permeability layer were monitored. The variation in hydraulic head across the low permeability layer is expected to be a determinant of conditions in the underlying soil. Desaturation will depend on the hydraulic conditions applied to the column and whether air can enter the system. Conditions applied to the column included air access and no air access.

The extrapolation of laboratory studies to field situations is difficult because of differences between the soil pore systems of the packed column and the in situ soil (Bouma, 1975). Laboratory studies also differ because they are conducted under isothermal conditions and are constrained by time limitations. However the purpose of this study is not to simulate field clogging, *per se*, but to obtain a greater understanding of such processes and predict possible implications of the clogging phenomenon.

3. THEORY OF SURFACE SEALING

Darcy's law for both saturated and unsaturated steady flow of water through soil is given by

$$q = -K \nabla H \quad (1)$$

where q is the rate of flow through a unit cross sectional area, K is the hydraulic conductivity of the soil and H is the hydraulic head. H may be given by $h+z$, where h is the pressure head and z is the elevation (or gravitational) head above some datum.

In a layered soil where the upper layer is of lower permeability than the underlying soil, steady state conditions require that the flux through the restrictive upper layer or crust, (q_c) be equal to the flux through the underlying bulk soil, (q_b).

$$q_c = q_b \quad (2)$$

or

$$K_c \left(\frac{dH}{dz}\right)_c = K_b \left(\frac{dH}{dz}\right)_b \quad (3)$$

where K_c , $\left(\frac{dH}{dz}\right)_c$, K_b and $\left(\frac{dH}{dz}\right)_b$ refer to the hydraulic conductivities and hydraulic head gradient of the crust and underlying bulk soil respectively.

Flow through such a layered soil is illustrated in Fig 1 and is given by

$$q = K_c \left(\frac{H_w + z_c - h_i}{z_c} \right) \quad (4)$$

where H_w is the positive hydraulic head above the layer caused by ponded water, z_c is the thickness of the layer and h_i is the pressure head in the soil directly beneath the layer. The downward infiltration rate into the underlying soil will be less than K_{sat} of this soil when the restrictive layer has a sufficiently small hydraulic conductivity. In this case, a negative pressure head may develop in the soil directly beneath this restrictive layer. Provided that the water table and associated capillary zone are deep, then the flow in the subsoil will be due to gravity alone and thus at a unit hydraulic gradient (the case shown in Fig. 1). The crust remains saturated even while the underlying soil is at negative pressures as long as the air entry value for the crust is greater than the pressure head of the underlying soil. This is illustrated for a hypothetical crust and underlying bulk soil in Fig. 2. Watson and Whisler (1977) reported that a sufficiently thick low permeability layer will cause soil water pressures to become negative beneath such layers and where pressures of the underlying soil are less than their air entry value (h_{aeV}) air will enter the profile laterally and the underlying subsoil will commence to desaturate given adequate air access.

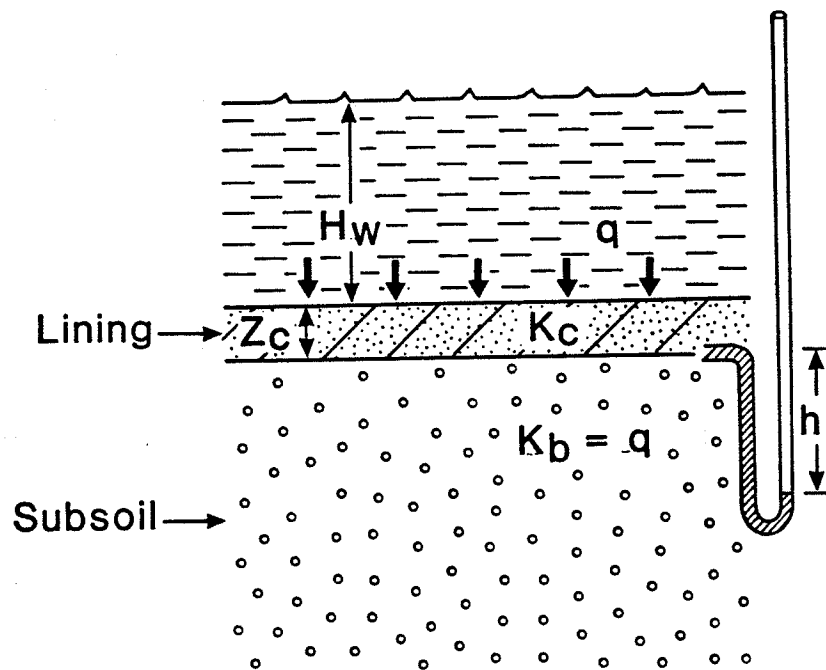


Fig. 1. Schematic diagram showing flow through a layered soil profile with a low permeability crust

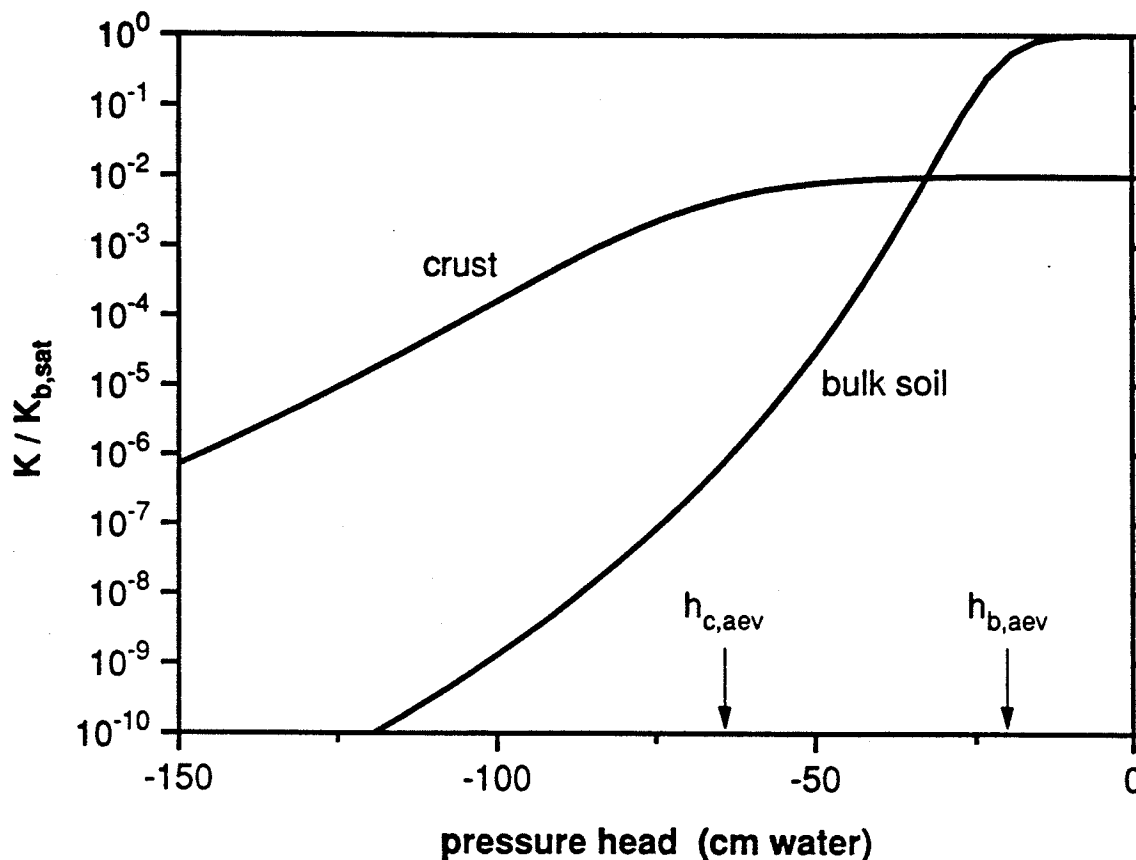


Fig. 2. Dependence of hydraulic conductivity, K , of a hypothetical crust and underlying bulk soil showing air entry values for the crust, $h_{c,aev}$, and bulk soil, $h_{b,aev}$ as well as the reduction of K_b below K_c . Hydraulic conductivities are given relative to saturated hydraulic conductivity of the bulk soil, $K_{b,sat}$

The air entry value of pressure head is critical because at pressures below this value there is a drastic reduction in K , and consequently in flow rates. Due to the sigmoidal nature of the $K(h)$ curve, the greater proportion of the reduction in conductivity occurs over a very small range in h (Fig. 2). The unsaturated hydraulic conductivity of the underlying soil at steady flow will be equal to the infiltration rate out of the system where there is free drainage and a unit hydraulic gradient. Equation (4) requires an estimate of h_i in order to calculate q . The value of h_i is found by trial and error using the known function $K(h)$ (Watson and Whisler 1977).

The hydraulic resistance of an impeding layer is obtained by Darcy's law applied to the layer and is defined as

$$q = \frac{K_c \Delta H}{z_c} = \frac{\Delta H}{R_c} \quad (5)$$

where

$$R_c = \frac{z_c}{K_c} \quad (6)$$

The hydraulic resistance may be obtained by dividing the head loss by the flow rate per unit area if the conductivity of the lining is unknown.

4. EXPERIMENTAL PROCEDURE

The PVC column used in this study was 80 cm long with an internal diameter of 6.3 cm. A 4 cm layer of 3 mm diameter glass beads was placed at the bottom of the column as a saturated support for the soil situated above. The interface between the beads and soil was supported and screened with steel mesh and fine gauze. A coarse material which constituted the "slot" material of the recharge basin at Boundary Creek (Johnston 1993) was chosen as the underlying bulk soil. A 62 cm layer of the bulk soil was hand packed to the measured dry bulk density of the field samples which was 1.59 g cm^{-3} . Four strain gauge absolute pressure transducers and associated tensiometer cups were installed laterally along the column to measure hydraulic head distributions. An auxiliary pressure transducer was used to measure ambient air pressure during the times of recording. The pressure transducers were linked to a voltage regulated power supply which was maintained at 5 volts and hydraulic heads were measured with a digital multimeter.

The column was sealed to be air tight after being purged of entrapped air and run to determine the hydraulic properties of the coarse material. This case will be referred to as "system A" in the following discussion. Calibration of the pressure transducers was performed at various surface heads under conditions of no flow within the column.

After the initial tests with coarse sand, the sand column was modified with the introduction of a discrete 5 cm thick layer of finer textured soil. The soil was obtained from the field site at a depth of 0.5 m below the bottom of the basin and constituted the limiting layer reported by Johnston (1990). The layer was hand packed to a field measured dry bulk density of 1.55 g cm^{-3} . A mean hydraulic impedance of this layer was determined from hydraulic gradients within this layer to be 0.1 days by equation (6). The final tensiometer cell was installed into the finer textured layer and a similar calibration was performed to relate output voltage and head. A 5 mm tube was fitted within the column wall at a depth of 0.5 cm below the interface between the fine and coarse soils to allow for air access during the latter stages of experimentation. At this stage, it was necessary to remove and repack the fine textured lining due to a rupture in the layer caused by entrapped air. Although the lining was repacked in a similar fashion, the hydraulic conductivity of the layer was found to be far less than that of previous runs. It appeared that fines were forced into suspension during the rewetting of the lining and later deposited as a thin layer on the surface. The case of a limiting layer situated above a coarse textured soil under the condition of no air entry will be referred to as "system B", whilst the condition of air entry will be referred to as "system C".

The column was operated for a variety of surface heads with the inlet head always well above the top of the column. The outlet head was positioned at varying locations along the length of the column. Relative hydraulic conductivities of various portions of the column (termed K_1 , K_2 , K_3 , K_4) were determined from head measurements using Darcy's law applied to each increment. The overall hydraulic conductivity of the column was calculated from the imposed head gradient and measured flow rate, again using Darcy's law. Flow of water through the column was vertically downward. The general arrangement of the soil column and associated auxiliaries are shown in Fig. 3.

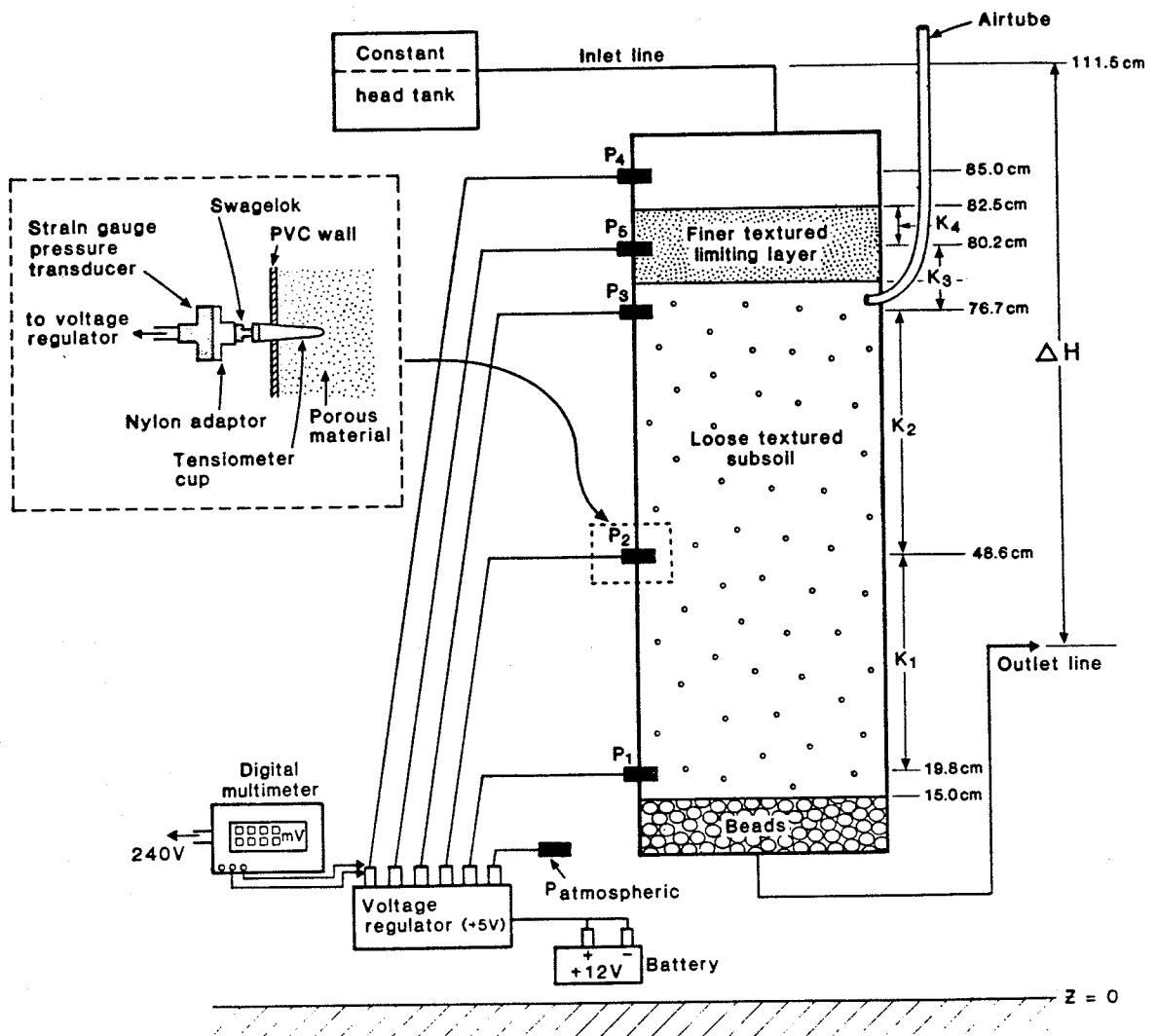


Fig. 3. Diagram showing the arrangement of the experimental column

4.1 Hydraulic Properties of the Porous Media

Figure 4 illustrates the particle size distributions of the porous materials used in the column study. The fine textured soil may be classified texturally as a sandy loam soil, whilst the underlying soil may be classified as a medium to coarse sand.

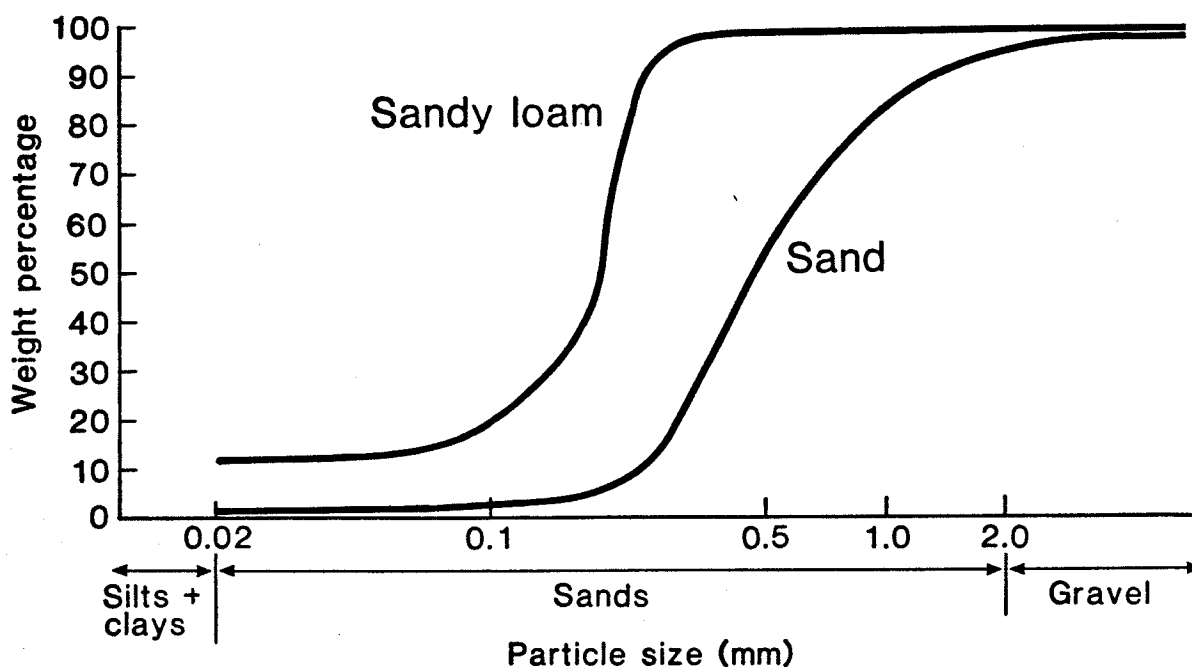


Fig. 4. Particle size distributions of the sandy loam and coarse sand used in the experimental column

4.2 Time Response of Tensiometer Cells

The response times for the tensiometer cells within the column and associated transducer devices were measured for a variety of changes in surface head which would occur over the course of the experiment. Incremental changes in head of up to 66 cm indicated that a period of up to 10 minutes was required (Fig. 5) for equilibration to occur within the column. Henceforth, an appropriate time delay was allowed prior to reading pressures to account for the time response factor.

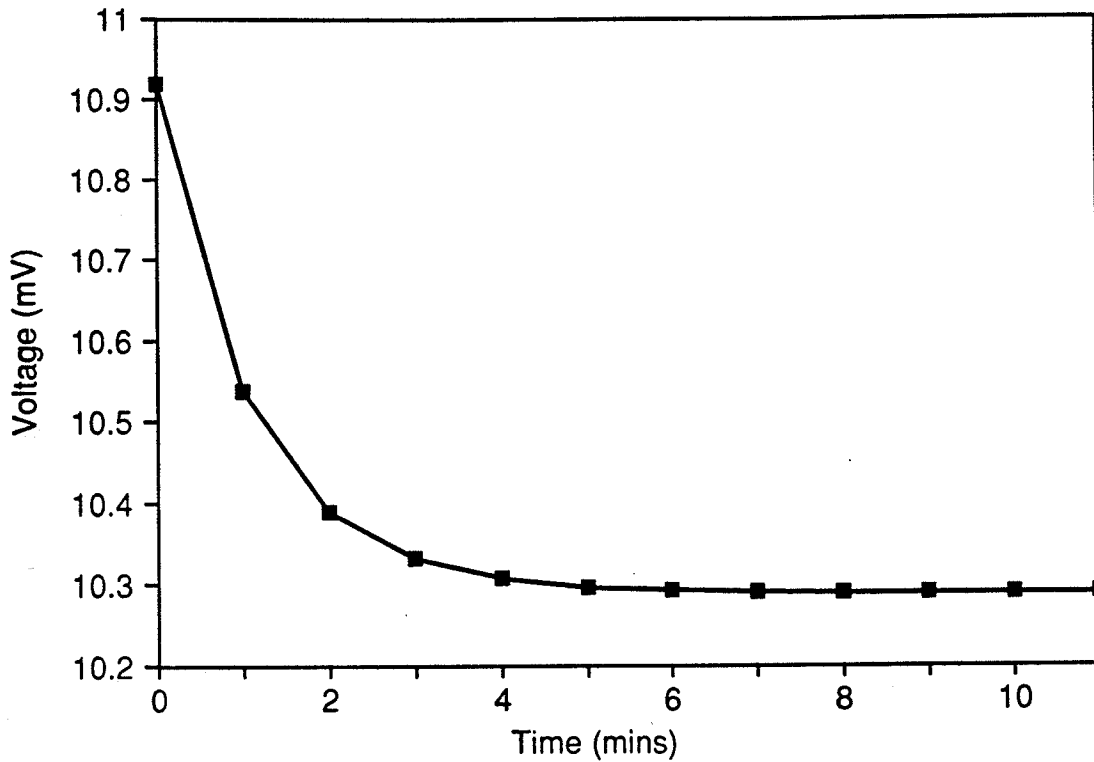


Fig. 5. Temporal response of pressure transducer tensiometer to a step change in pressure

4.3 Calibration of the Pressure Transducers

Calibration for each of the pressure measuring devices was performed by recording the voltage measured for a variety of surface heads under no-flow conditions. The calibration involved equating the voltage with the hydraulic head at the position of the tensiometer within the column. This procedure was run twice in successive days (i.e. runs A and B). Variations in ambient pressure during runs were recorded and accounted for in the calibration. This was done by adding or subtracting the mean atmospheric pressure difference as compared to the standard for each transducer in the calibration runs and during all the preceding runs. An ambient pressure (recorded as a voltage) of 10.201 mV (i.e. the mean of run A) was chosen as the standard pressure. The calibration data recorded during runs A and B for each tensiometer are given in Fig. 6. The calibration equations for each pressure transducer were determined and may be given as

for transducer P1: $E = \frac{V - 9.980737}{0.009575}$ $R^2 = 0.999863$ (7)

" P2: $E = \frac{V - 9.846662}{0.009674}$ $R^2 = 0.99820$ (8)

" P3: $E = \frac{V - 9.551119}{0.009690}$ $R^2 = 0.999861$ (9)

" P4: $E = \frac{V - 9.486389}{0.009696}$ $R^2 = 0.999619$ (10)

" P5: $E = \frac{V - 9.560282}{0.009906}$ $R^2 = 0.998878$ (11)

where E is the elevation of the surface head (cm) and V is the recorded voltage (mV) adjusted for differences from the standard air pressure.

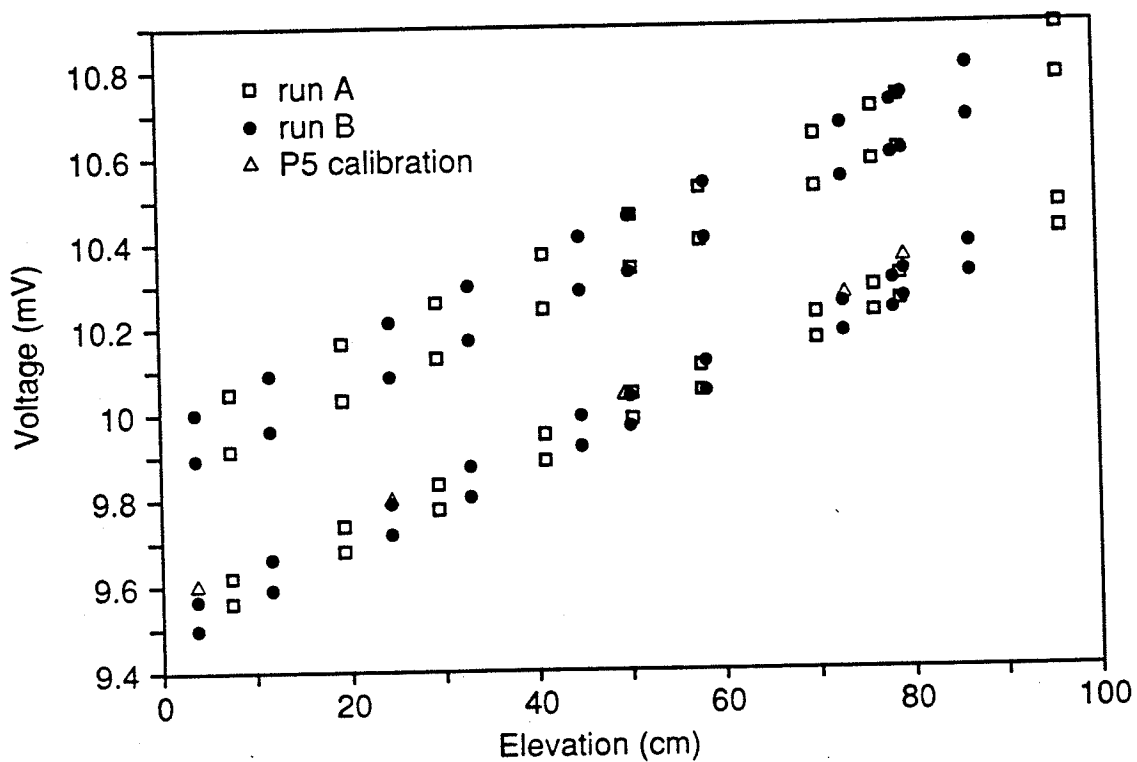


Fig. 6. Calibration data for pressure transducers

A regression analysis performed on the calibration data indicates that an excellent fit exists between surface head and voltage (Fig. 6). Statistical analysis of these data indicates that maximum likely error in the total head is less than ± 0.5 cm. Calibration of the final tensiometer was done at a later date, following the installation of the finer textured layer, and is also given in Fig. 6. It is interesting to note that the slopes of the calibration lines are virtually identical (at close to 100 cm mV^{-1}) and represents the response of the strain gauge to changes in surface head. The positioning of these regression lines denoted by the intercept of the regression lines reflects the varying voltage characteristics of each individual strain gauge transducer.

5. RESULTS AND DISCUSSION

5.1 Steady State Flow At Various Head Gradients

Figure 7 illustrates the relationship between head gradient and flow for systems A, B and C. Systems A and B exhibit a linear trend whose slope is proportional to the mean soil permeability within the column. System A shows a greater increase in flow for a corresponding increase in head gradient due to the greater permeability of the homogeneous coarse textured soil. For system B, the mean saturated hydraulic conductivity of the coarse soil was measured at about 27 m day^{-1} , whilst that of the fine textured layer was determined to be 0.56 m day^{-1} from hydraulic gradients within the column (Table 1). Prior to the installation of the tensiometers the saturated hydraulic conductivity of the coarse soil was found to be 43 m day^{-1} . This reduction in hydraulic conductivity of the coarse soil probably resulted from the disturbance of the column during tensiometer installation. The lining of fine textured soil reduced the mean hydraulic conductivity of the column to about 5 m day^{-1} for system B. Deviations from the linear relationship between flow rate and head gradient occurred in both systems A and B. These are thought to be due to the following causes:

- (i) installation of tensiometer resulting in entrapped air within the column causing a reduction in flow rates in run 1 of system A (Fig. 7a).
- (ii) a suitable period for the settling of soil grains within the column was not allowed following the addition of the fine textured layer prior to measurements being taken. This resulted in flow rates far higher than those observed during latter stages. Data

from run 5 is thought to belong in this category. Run5 was the first of a series of runs performed in one day and it is thought that the settling factor would account for its location on the graph (Fig. 7a).

In the case of system C (with air access) a dramatic reduction in flow rates occurred due to the repacking of the lining. It is thought that the flow-hydraulic gradient relationship is not linear and exhibits hysteresis. The first of the runs for system C (run 13) appears to be affected by air entrapment within the column. Hydraulic conductivity is much less than in subsequent runs (see Table 1 and Fig. 7b). For runs 14 - 16 which followed, flow rates increased approximately linearly with increasing head gradient as expected for conditions of constant hydraulic conductivity. The further increase in gradient in run 17 produced a very large decrease in flow rate and reduction of hydraulic conductivity in the coarse sands. This is a result of pressure head in the coarse sand falling below h_{aeV} . This feature is evident from the pressure distribution data which will be discussed below. Hysteresis appears to influence the following run 19 where the head gradient decreased but flow rates remained much lower than the corresponding run under conditions of increasing head gradient - run 14 (Fig. 7b).

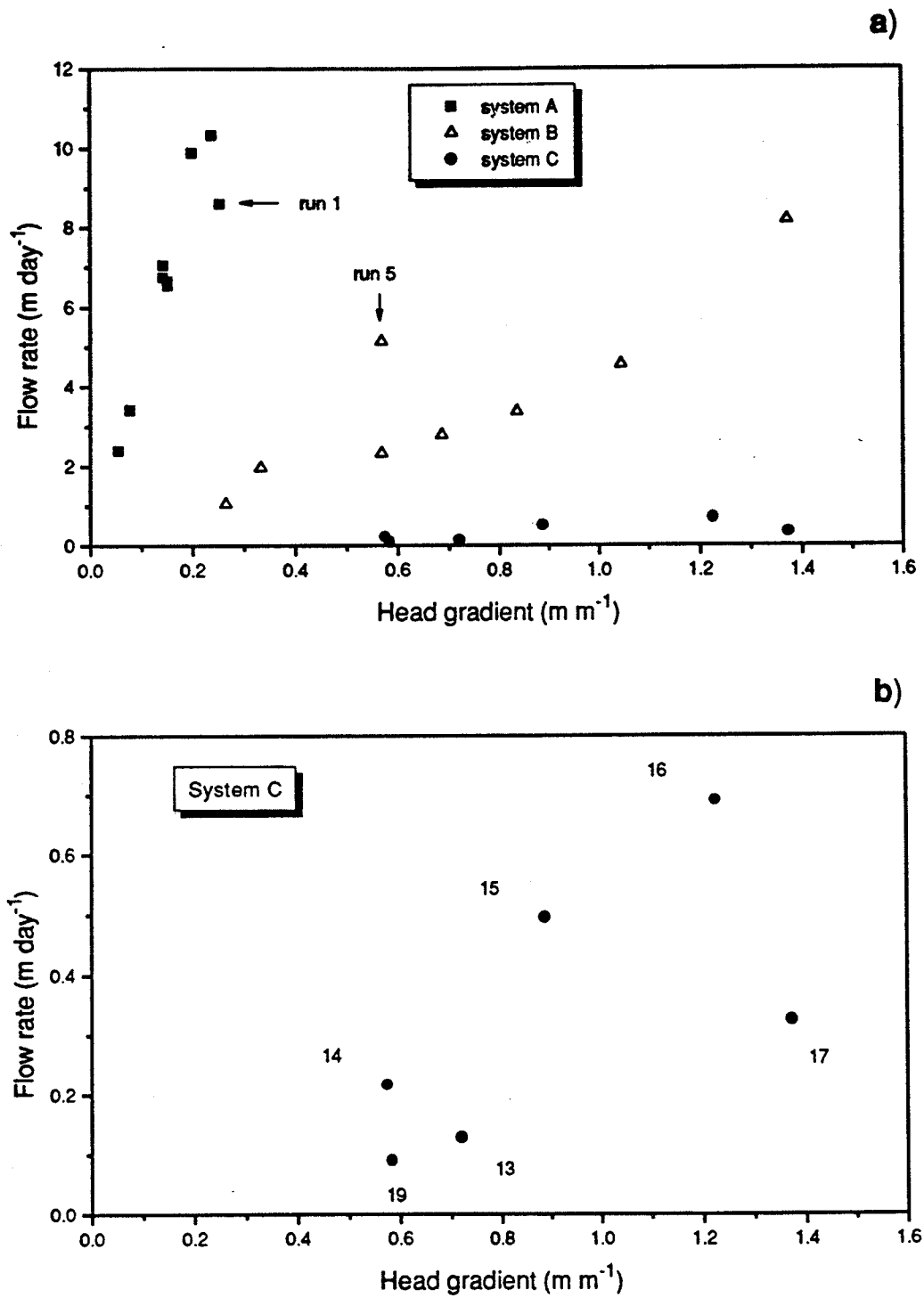


Fig. 7. Relationship between flow rate and head gradient for all experiments - a) systems A, B and C and b) system C only. Numbers associated with data points are the run numbers given in the text and Table 1

Table 1. Flow rates and calculated hydraulic conductivities in flow experiments

Run Number	ΔH (cm)	VH	K	Q	K ₁	K ₂	K ₃	K ₄	K _(coarse)	K _(fine)
m day ⁻¹										
SYSTEM A										
3	20.3	0.32	30	9.8	40	59	-	-	47	-
SYSTEM B										
4	17.8	0.26	3.9	1.0	30	29	3.0	0.17	29	0.39
5	38.3	0.57	9.1	5.1	27	31	5.1	0.50	29	1.1
6	22.4	0.33	5.9	2.0	26	34	4.9	0.29	29	0.66
7	38.3	0.57	4.0	2.3	23	28	4.5	0.17	25	0.41
8	46.3	0.69	4.0	2.8	23	29	4.4	0.17	26	0.41
9	56.4	0.84	4.0	3.3	25	29	4.0	0.17	27	0.40
10	70.5	1.04	4.3	4.5	23	26	4.0	0.19	24	0.44
11	92.6	1.37	6.0	8.2	22	25	4.1	0.29	23	0.66
SYSTEM C										
13	48.6	0.72	0.18	0.13	3.9	8.0	-	-	5.2	0.016
14	38.8	0.57	0.38	0.22	8.9	15	-	-	11.2	0.033
15	59.9	0.89	0.57	0.50	29	14	-	-	18.8	0.050
16	82.7	1.23	0.56	0.69	28	1.0	-	-	1.97	0.064
17	92.7	1.37	0.24	0.32	3.7	0.33	-	-	0.61	0.030
19	39.4	0.58	0.15	0.090	4.3	13	0.19	0.0056	6.4	0.014

The hydraulic properties of the soil column for the various scenarios are given in Table 1 for runs 3 to 19. Measurements from run 12 were withdrawn due to problems of air entry into the column following the installation of the air access tube. Furthermore, flow rates during run 18 were not measured. Relative conductivities in the fine textured layer must be treated with suspicion during system C experiments due to problems within the layer around tensiometer P5.

5.2 Hydraulic Head Distributions of Uniform Soil

Hydraulic head distributions for the case of steady flow for a range of hydraulic heads were measured for the initial case of uniform soil (system A) for the following reasons:

- (i) as a final check of the calibration equations, prior to proceeding with systems A and B.
- (ii) to determine the uniformity of the soil within the column. Non-uniform packing density should be recognisable by varying hydraulic gradients caused by restricted flows.
- (iii) particular attention was given to the hydraulic gradients at the top of the column (around P4) where a zero gradient is expected within the ponded layer of water directly above the soil.

Figure 8 shows the hydraulic head distribution at various times within the column for an applied head difference of 20.3 cm (run 3). Gradients (and consequently relative conductivities) within the column are relatively uniform (Table 1) following a period of equilibration (from 2:39 to 3:42 pm). The reason for the discrepancy between the hydraulic head difference applied (20.3 cm) and the hydraulic head difference measured within the column (14 cm) is unclear but may be due to resistances in the outlet of the column or fluctuations in the outlet head elevation. The discrepancy is not due to errors in the calibration but does give rise to the difference between the K of the column calculated from the imposed head gradient and values of hydraulic conductivity determined internally within the column. (In all other runs, there was excellent agreement between applied head difference and that measured in tensiometers. The discrepancy between applied and observed difference ranged from -0.8 to 1.4 cm while most were in the range -0.4 to 0.7 cm.) Although a hydraulic gradient was observed between the top tensiometer and water ponded on the top of the column, the head difference was only slightly larger than

measurement errors. The overall uniformity of the gradients allowed the experimentation to proceed with the application of a surface lining.

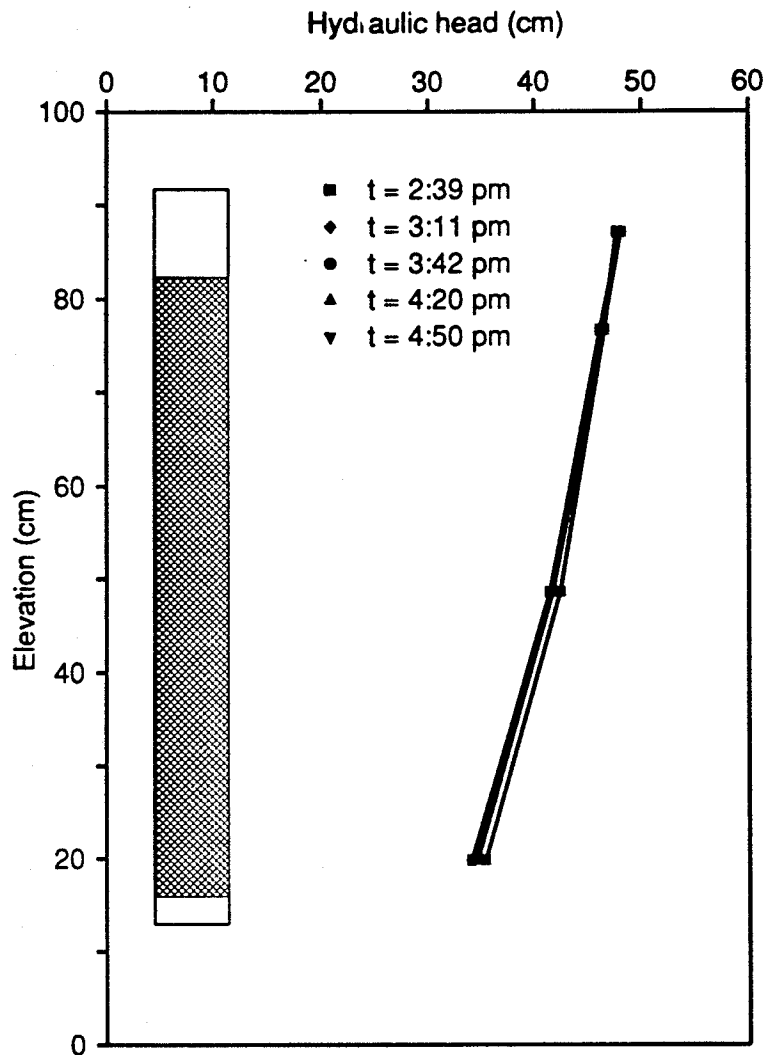


Fig. 8. Hydraulic head distribution in the column for run 3 of system A

5.3 Hydraulic Behaviour of a Clogged Soil in the Case of No Air Access

Flow rates and hydraulic heads (and corresponding pressure heads) were monitored during 5 runs. The inlet head was fixed ($z=111.8$ cm) and the outlet head dropped incrementally over the length of the column prior to each run. The hydraulic head differences ranged from 38.3 cm (run 7) to 92.6 cm (run 11). Pressure and hydraulic head distributions are each displayed in separate figures for the combined data sets of runs 7, 9 and 11. Results from runs 8 and 10 are not displayed, however these cases occupy positions intermediate

between those displayed. Flow rates, mean hydraulic conductivities and relative conductivities for each run are given in Table 1.

Pressure head distributions (Fig. 9) reflect the location of the mobile outlet head and the fixed inlet head, with the location of zero pressure head indicating the position of the outlet head. Maximum positive pressures occur at the top of the column, and rapidly decrease with depth to a maximum negative value at the interface between the lining and the subsoil. Pressure head gradients are uniform in the coarse material. Capillary effects were not observed in the lowermost pressure transducer. The effect of reducing the applied head at the bottom of the column (increasing the applied head difference) is to make the pressure head at the base of the fine textured layer more negative. Pressure distributions are similar to those encountered in related studies (Day and Luthin 1953, Behnke and Bianchi 1965). The lowest pressure head in the coarse sand was -39 cm at tensiometer P3 in run 11 (see Fig. 9). The hydraulic conductivity of the coarse sand was unaffected by this low pressure head (Table 1).

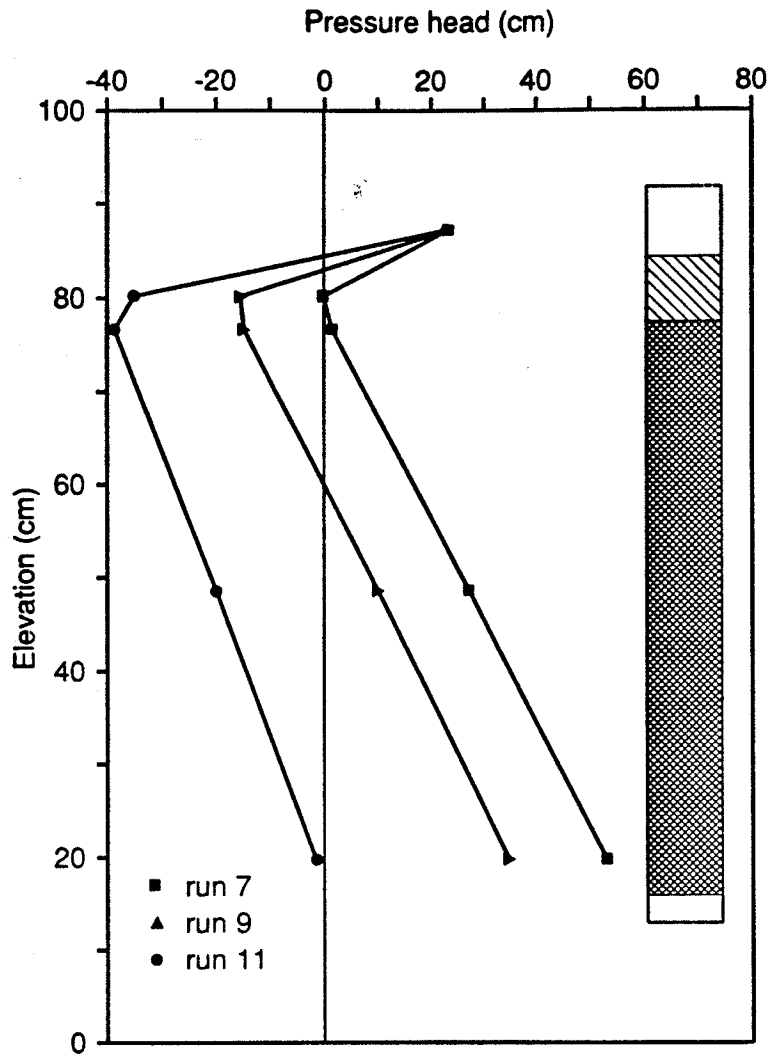


Fig. 9. Pressure head distribution for runs 7, 9 and 11 of system B

Figure 10 shows that the hydraulic head gradient within the lining adjusted by increasing with increasing applied head difference. It is important to note that heterogeneity within the finer textured layer is believed to result in the varying gradient within this layer (i.e. $K_4 \ll K_3$). The difference in K may also arise because of the finite size of the tensiometer and the placement of P3 in the top of the coarse sand (Fig. 3). The hydraulic gradient within the subsoil is very small but increasing (e.g. see run 11), indicating that hydraulic conductivity remains unchanged in this zone (Table 1).

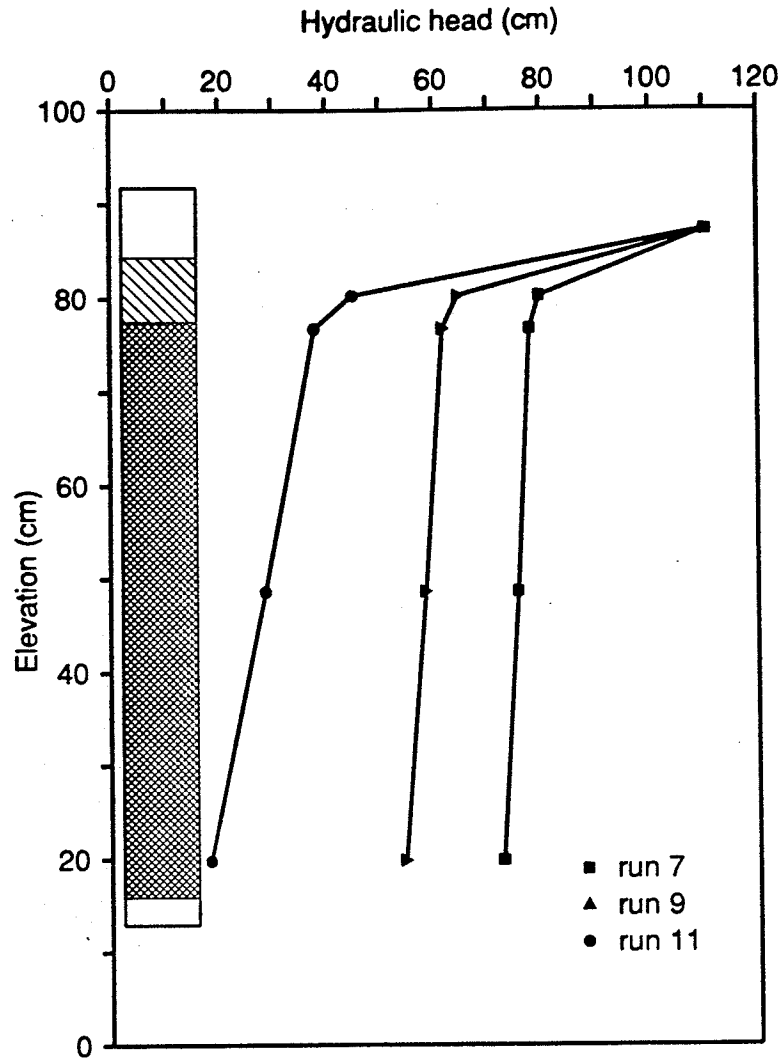


Fig. 10. Hydraulic head distribution for runs 7, 9 and 11 of system B

5.4 Hydraulic Behaviour of a Clogged Soil in the Case of Air Access

A procedure similar to that of system B was followed during system C, whereby flow rates and head distributions were recorded over 5 runs. The inlet head remained fixed at 111.5 cm and the outlet head was lowered in stages. The applied head difference ranged from 38.8 cm (run 14) to 92.7 cm (run 17). The inlet head was raised after run 17 to provide the conditions for run 19. The results have been displayed in a similar fashion to those of the previous case for runs 15, 17 and 19. A direct comparison may be made between systems B and C by comparing the data of runs 7/19 and runs 11/17. Flow rates and hydraulic conductivities for each run are given in Table 1. Problems within the lining resulted in false readings from the transducer P5, located in the centre of the fine textured layer. For

these reasons data from this transducer have been omitted from Table 1, but are retained in the Figures 11 and 12 although they should not be regarded as accurate. A restoration of the lining layer allowed one final run to occur with P5 giving satisfactory results. Water initially filled the air entry tube prior to commencing system C runs and it was not until a head difference of 59 cm (run 15) was applied that air entered the soil column.

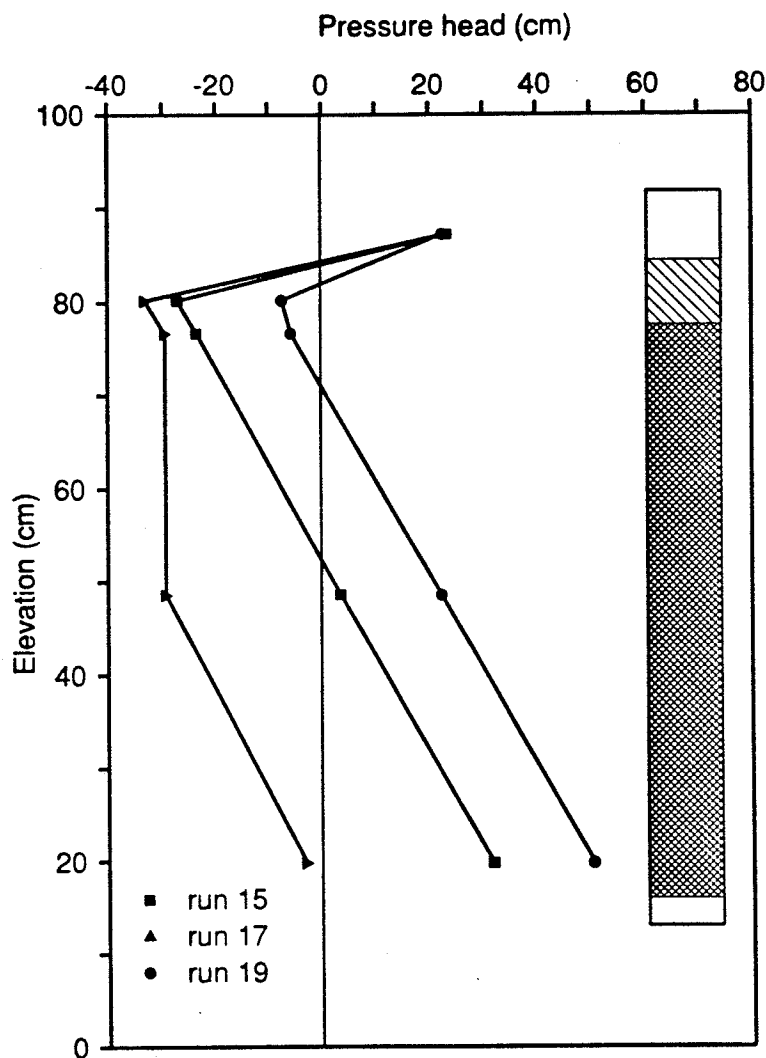


Fig. 11. Pressure head distribution for runs 15, 17 and 19 of system C

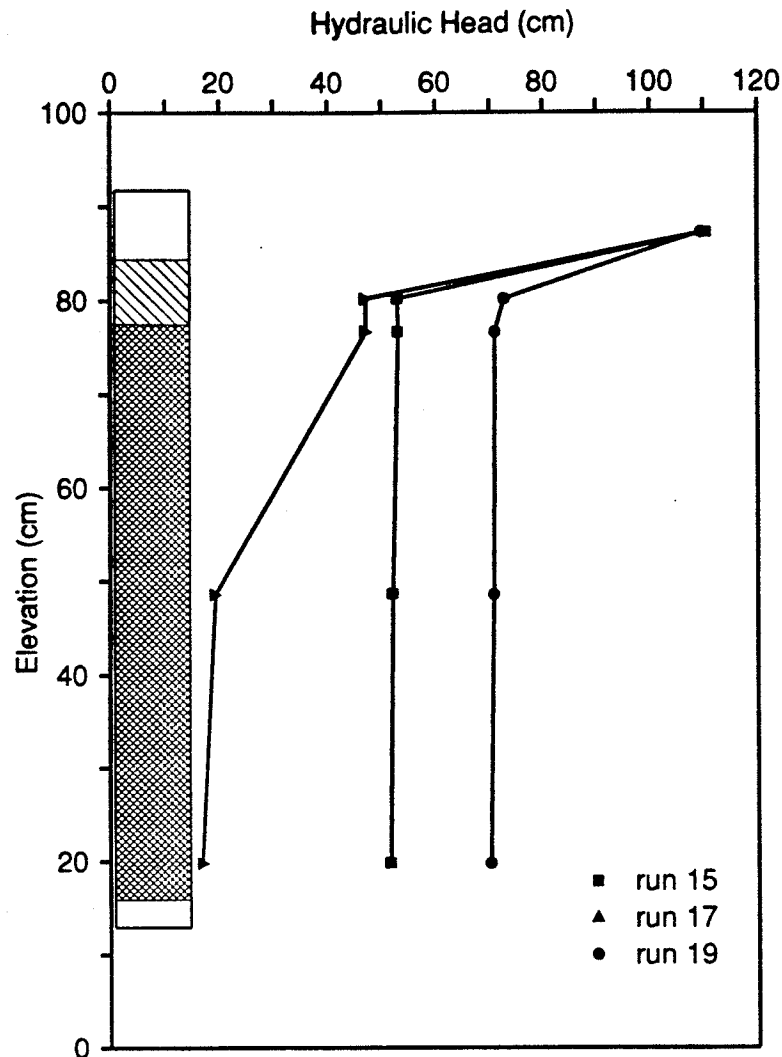


Fig. 12. Hydraulic head distribution for runs 15, 17 and 19 of system C

Some caution needs to be exercised in interpreting the hydraulic conductivities of the coarse sand shown in Table 1. Head differences are very small in the coarse sand in runs 13, 14 and 19 - the head differences between the tensiometers were only 0.4 - 0.7 cm, about the same order as measurement errors. This introduces large uncertainties in K_1 and K_2 for these runs. Similar uncertainty exists in K_1 for runs 15 and 16. It therefore can not be concluded that there has been any change in the K_{sat} of the coarse sand from system B to system C.

Pressure head distributions (Fig. 11) in the fine textured layer appear very similar to those of the no air entry cases (Fig. 9) with pressures reaching a maximum negative value at the soil interface. Pressure distributions during runs 15 and 19 appear virtually identical to

those of system B however conductivities (and corresponding flux rates) have been significantly reduced. In run 17, however, pressure head becomes constant over the upper part of the subsoil below the lining. This feature is pronounced in the hydraulic head profiles (Fig. 12) whereby a significant head gradient is observed within the coarse layer for the first time since the fine textured layer was applied. This signifies a marked reduction in the unsaturated conductivity of the coarse soil at a pressure head corresponding to -29 cm. This low conductivity zone appears to extend significantly below transducer P2 in run 17 as an increased gradient is also observed in the lowermost zone. The first reduction of conductivity appeared in run 16 where there was a marked reduction in K_1 . The K of the column as a whole remained unchanged though because of an apparent increase in K of the fine textured layer (Table 1). There were further significant reductions in hydraulic conductivity of the coarse sand in run 17. These reductions in hydraulic conductivity of the coarse sand occur at a pressure head of -29 cm for runs 16 and 17, corresponding to the air entry value of pressure head. A pressure head of -24 cm in run 15 has apparently not caused any reduction in hydraulic conductivity because it is above the h_{ae} . Table 1 displays this marked reduction in conductivity in the subsoil region where both K_1 and particularly K_2 have declined. In particular, K_2 decreases from 14 m day^{-1} in run 15 to 0.32 m day^{-1} in run 17. Importantly, it can also be seen that there has been an apparent decrease in the K of the fine textured layer between run 16 and run 17 which contributes to the lower flow rate. The decrease in K of the fine layer may be a result of partial desaturation but the possibility that the K is dependent on flow rate can not be excluded. The fine textured layer was observed to be somewhat unstable during the flow experiments, especially for system C, and the trend for K of the fine layer to increase with flow rate in runs 14 to 16 suggests flow rate may control packing and the development of larger pores through this layer.

The lower flow rates in run 19 compared to run 14 is consistent with the effects of hysteresis during the wetting up of the column for run 19 with mainly the fine textured layer having a lower hydraulic conductivity (Table 1). There is, however, a strong possibility that this hysteresis is artificially produced by air trapped within the column due to inadequate air access. Resetting of the tensiometer P5 may also have disturbed the fine textured layer.

5.5 Problems Associated with the Fine Textured Layer

Although the study was aimed at observing the effects of a homogeneous clogging layer above a coarser textured subsoil, hydraulic gradients within the column lead to the conclusion that the lining is not uniform. During the "wetting up" phase it seems that sediment was released from soil into suspension resulting in the finest sediments being deposited at the top of the column after settling. This variability in hydraulic conductivity within the lining is not of any real concern as the overall processes which occurred in the column appear to be largely unaffected by the non uniformity.

A cause of greater concern, however, occurred during the installation of the air access tube prior to the commencement of system C. An air bubble is believed to have ruptured the fine textured layer causing a short term increase in flow rates and increased turbidity of the outlet water. However it appears that the soil surrounding tensiometer P5 was displaced during the repacking of the fine textured layer, resulting in false readings between runs 14 and 17 from this pressure transducer. The situation was rectified with the removal of the transducer P5 and subsequent refilling of the finer textured soil. This allowed time for one final run to occur with the condition of air entry (run 19). Unfortunately, the fine textured layer appears to have been unstable during the series of runs. The evidence for this is the apparent relationship between flow rate and hydraulic conductivity of the layer. This makes it difficult to interpret the reason for the reduced hydraulic conductivity of the fine textured layer in run 17 and therefore the relative importance of the unsaturated coarse sand in controlling flow rates through the column.

6. CONCLUSIONS

The addition of a surface lining above a coarse textured soil has been shown to significantly reduce flows through the soil system. Furthermore, flows are reduced even further at some critical pressure head whereby the underlying soil is allowed to desaturate, resulting in a marked decrease in hydraulic conductivity.

Air access into the column significantly reduced the flux of water through the column at a critical head difference of 93 cm. At this stage a large hydraulic gradient within the subsoil occurred beneath the lining, signifying a marked reduction in the hydraulic conductivity of the subsoil in the order of 1 to 2 orders of magnitude. This reduction corresponded to a pressure head in the coarse textured soil of approximately -29 cm, thought to be the air entry pressure of this soil. In the experiments where air was not allowed to enter the column, the coarse sand maintained its high hydraulic conductivity even though pressure head was lower than the air entry value.

In concluding, it has been shown that the hydraulic processes within the subsoil may dominate the flows through the column following clogging. In recharge basin operations it seems imperative therefore that the hydraulic characteristics of the basin material be known and regularly monitored in order to maximise infiltration rates to the groundwater.

8. ACKNOWLEDGEMENT

The work described here was done while Paul Pavelic was a summer student at the Floreat Park laboratories of CSIRO Division of Water Resources.

8. REFERENCES

- Behnke, J.E. (1969) Clogging in surface spreading operations for artificial groundwater recharge. *Water Resour. Res.*, 5:870-876.
- Behnke, J.E. and Bianchi, W.C. (1965) Pressure distributions in layered sand columns during transient and steady-state flows. *Water Resour. Res.*, 4:557-562.
- Bouma, J. (1975) Unsaturated flow during treatment of septic tank effluent. *J. Environ. Eng. Div., ASCE*, 101:967-983.
- Bouwer, H. (1982) Design considerations for earth linings for seepage control. *Groundwater*, 20(5):531-537.
- Clark, G.B. and Kneeshaw, M. (1983) Artificial recharge in the Pilbara, Western Australia. In Papers of the Hydrology and Water Resources Symposium, 1983, Hobart 8-10 November.
- Day, P.R. and Luthin, J.N. (1953) Pressure distribution in layered soils during continuous water flow. *Soil Sci. Soc. Amer. Proc.*, 17(2):87-91.
- Hazel, C.P. and Hillier, J.R. (1989) Artificial recharge in Queensland, Australia. In: "Artificial Recharge of Groundwater", (Eds. A.I. Johnston and D.J. Finlayson). Proc. Int. Symp., Anaheim, Calif., 1988. pp 518-527.
- Johnston, C.D. (1990) Development of design theory for artificial recharge works. Final Report, AWRAC Partnership Research Project P86/20. CSIRO Division of Water Resources, Perth.
- Johnston, C.D. (1993) The 1990 artificial recharge trials at Boundary Creek: the testing of a slot excavated through a shallow impeding layer. CSIRO Division of Water Resources, Technical Memorandum 93/1 (CSIRO Division of Water Resources, Canberra).

- O'Shea, J.A. (1967) Replenishment of underground water supplies - Burdekin Delta, Queensland. *Civ. Eng. Trans., Inst. Eng., Aust.*, CE9:117-126.
- Schuh, W.M. (1988) In-situ method for monitoring layered hydraulic impedance development during artificial recharge with turbid water. *J. Hydrol.*, 101:173-189.
- Schuh, W.M. and Shaver, R.B. (1989) Hydraulic effect of turbid water infiltration through a shallow basin. In: "Artificial Recharge of Groundwater", (Eds. A.I. Johnston and D.J. Finlayson). Proc. Int. Symp., Anaheim, Calif., 1988. pp 85-96.
- Shainberg, I. and Singer, M.J. (1986) Suspension concentration effects on depositional crusts and soil hydraulic conductivity. *Soil Sci. Soc. Amer. J.*, 50:1537-1540.
- Watson, K.K. and Whisler, F.D. (1977) Profile desaturation during sediment deposition in a groundwater recharge trench. *J. Hydrol.*, 33:397-401.