Hydraulics Research
Wallingford

EVALUATION OF AN AIR-ENTRY PERMEAMETER

FOR USE IN INVESTIGATIONS OF GROUNDWATER FLOW BENEATH FLOOD EMBANKMENTS

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ABSTRACT

An air-entry permeameter for the in-situ measurement of the coefficient of permeability of soils has been constructed and tested at Hydraulics Research.

The problems involved with in-situ permeability measurements on natural soils have been discussed, particularly in the context of groundwater flow beneath flood embankments. The air-entry permeameter has been examined as an alternative to other existing techniques. Reasons to explain some of the problems encountered have been proposed. Attempts to modify the equipment have been explained. Various testing techniques have been briefly described and some of their relative merits discussed. A comparison of the results with those derived from other methods have been made and discussed.

Finally, the conclusions of the work have been brought into the context of the use of the results by engineers in order to evaluate the potential for groundwater flow beneath flood embankments.

CONTENTS

1 INTRODUCTION

1.1 Groundwater flow beneath flood embankments

Flood alleviation schemes often incorporate earth embankments to protect prime agricultural or developed areas of the flood plain. The embankments themselves, if suitably constructed, are relatively impermeable but the ground beneath them may be permeable. River flood plains are commonly built-up of terraces of permeable sands and gravels overlain by less permeable alluvial silts and clays.

As a result, significant groundwater flow can take place through the soil once a high head of water is maintained in the channel between the artificial banks of a flood alleviation scheme. Such a head of water will increase groundwater pressures which may be transferred through the permeable strata, forcing groundwater up to the surface and flooding the land inside the embankment. This may be considered as a partial failure of the embankment even though overtopping has not occurred.

The hydraulics of such a system must be considered during the design of flood embankments.

1.2 Role of the air-entry permeameter

In order to assess the possibility of this mode of failure at a specific location it is necessary to investigate the hydraulic properties of the soils concerned. One such important property is the vertical permeability of the material near the ground surface. If it is low, then the material will act as a capping layer preventing groundwater from reaching the surface from lower, more permeable, strata.

The air-entry permeameter is a device for measuring that permeability. It was introduced by Bouwer [1] as an alternative to techniques such as the double-tube method, infiltration gradient technique and others.

The advantages of the method are reportedly:

- speed
- the relatively small volume of water required
- there is no need to install piesometers or tensiometers in the soil to measure pressure gradients.

For these reasons it was selected for evaluation as part of the strategic research programme at Hydraulics Research into the problem of seepage beneath flood embankments.

1.3 Work carried out by HR

An air-entry permeameter was constructed at HR based on the design proposed by Bouwer [1]. Some modifications were introduced in order to refine the test method. The system was tested and was applied in the field on three separate areas of river flood plain loams of the Thames Valley. One area was also tested by two other methods of estimating the coefficient of permeability, for comparison, and some of the shortcomings of these methods were highlighted. The air-entry permeameter was also tested on a uniform sand deposit of high permeability.

2 MEASUREMENT OF PERMEABILITY

2.1 A note on permeability

The permeability of a given soil is usually expressed as the Darcy coefficient of permeability, k, which applies when the fluid concerned is water. The coefficient of permeability of a particular porous medium refers to the volume of water which will permeate through unit area of that medium in unit time under unit hydraulic gradient. As such, k is measured in units of velocity, viz:

$$L^3 L^{-2} T^{-1} = L T^{-1}$$

$$m^3/m^2/s = m/s$$

The permeability of a given soil is a property which depends upon many variables, such as the porosity, grain size, grain shape, compaction, structure and morphology of the soil. The permeability may vary considerably with relatively minor soil variations.

Natural soils ranging from clays to gravels exhibit permeabilities ranging between 10^{-10} and 10^{-1} m/s respectively - a range of nine orders of magnitude. Mixed deposits such as loams display overall characteristics of permeability dependent upon the clay/silt/sand fractions that comprise the soil, though the permeability is mainly governed by the finer fractions present in the soil.

The measurement of permeability involves the imposition of an artificial situation upon a soil and the measurement of its effect. The validity of the resulting permeability value will depend upon the applicability of the test to a real situation and upon the disturbance of the natural conditions due to that test.

It is inappropriate to expect a series of permeability tests to produce one single value corresponding to a true discrete permeability of a soil, within fine error limits. The coefficient of permeability of a soil is usually quoted within a range of at least one order of magnitude.

With these limitations in mind, permeability tests have a very important role in site investigations for many engineering projects.

2.2 The problem of the unsaturated zone

The saturated zone, beneath the water table, contains interstices which are filled with water and the pore pressures are positive with respect to atmospheric pressure. The measurement of the saturated coefficient of permeability (k_{sat}) within this zone is relatively straightforward. Techniques for accomplishing this using borehole tests are well documented [2].

The unsaturated zone, above the water table, contains interstices which are filled with both water and air resulting in pore pressures that are negative with respect to atmospheric pressure due to the effects of surface tension. Measurements of the unsaturated permeability (k_{unsat}) within this zone may be made but are not meaningful for engineering calculations.

This is because k_{unsat} is dependent upon the moisture content (the degree of saturation). The effective coefficient of permeability, k, increases with increasing moisture content until full saturation when

$k = k_{sat} = \text{constant}.$

The problem that engineers are faced with is - how to make measurements in the unsaturated zone to derive a value of permeability that is applicable when that zone becomes saturated. This is further complicated by the fact that we are concerned primarily with the vertical permeability which is typically less than, and often masked by, the horizontal permeability.

2.3 Outline of other possible techniques

Various techniques exist for deriving k_{sat} from measurements in the unsaturated zone but each technique suffers from certain disadvantages. A brief description of some of the documented methods of permeability testing in the unsaturated zone follows and some of their relative advantages and disadvantages are discussed.

2.3.1 Formula based on grain size [3]

Permeability formulae based on grain size characteristics are the easiest method of estimating the coefficient of permeability. Many formulae have been proposed but the simplest and most commonly used is the Hazen formula which states:

$$k = 0.01\, d_{10}^2, \quad \text{ms}^{-1}$$

where d_{10} is the grain size of which 10% of the particles are finer, measured in mm. This formula takes no account of the grading of the material or of its structure. It has been found to provide a reasonable estimate of the coefficient of permeability for uniformly graded filter sands but is not strictly applicable to fine alluvial deposits.

2.3.2 Laboratory permeameter [3]

This technique involves the removal of a soil sample from the field and the installation of the sample into a laboratory permeameter. A flow of water is then maintained across the sample under a set hydraulic gradient. The flow of water is measured and the coefficient of permeability may then be calculated according to Darcy's Law.

It is not possible to obtain a totally undisturbed sample from site. Very large errors may occur due to this disruption and re-packing of the sample.

2.3.3 Shallow well pump-in method [4]

This technique involves the drilling of a small auger hole into the soil to be tested. Water is then added to the hole and maintained at a constant depth. The dimensions of the auger hole, the water depth and the inflow/outflow rate are used to calculate the coefficient of permeability of the soil.

Advantages are that minimal equipment is needed and the test is very simple and easy to carry out on site. Disadvantages are that a long period of time may be required in order to achieve the steady state conditions required for the analysis. Also, flow from the well is predominantly horizontal and so the vertical permeability cannot be derived. Further disadvantages with this technique were discerned as discussed in Section 5.3.

2.3.4 Cylinder permeameter method [5]

For this method a hole is excavated and a cylinder is pushed into the base of the hole. The purpose of the cylinder is to isolate an area where flow may be considered vertical. Tensiometers are installed in the soil beneath the cylinder. A head of water is maintained in both the cylinder and the hole. When the tensiometers indicate that the wet-front has reached a known depth, the flow into the cylinder is measured. The coefficient of permeability may then be calculated using Darcy's Law.

Advantages are that it is not necessary to achieve steady state conditions. Disadvantages are that an instantaneous measurement of flow rate is required. Also the setting up of the test and the installation of tensiometers may take some time.

2.3.5 Infiltration gradient method [6]

This technique is a modified version of the cylinder permeameter method above. An inner and an outer cylinder are pushed into the ground and a head of water is maintained within them. Miniature piezometers are pushed into the ground within the wet zone to measure the hydraulic gradient. Again, the coefficient of permeability is calculated using Darcy's Law.

The advantage of this method is that any effects due to surface sealing at the water -soil interface are eliminated. The disadvantages are that a volume displacement is required for the piezometers to register and that they are likely to be difficult to operate on site.

2.3.6 Double tube method[7]

This method utilizes two concentric cylinders pushed into the soil. A head of water is maintained level in both tubes until a steady state flow condition is achieved. A drop in level in the inner tube is then allowed whilst maintaining the level in the outer tube. Both tubes are then topped up and steady state is achieved again. A drop in level in both tubes simultaneously is then allowed and monitored. Comparison of the rate of outflow between the inner tube only and both tubes may be used with a theoretical flow factor to produce a value of the coefficient of permeability.

Advantages are that the equipment needed is very simple and easy to use on site. Disadvantages are that a large quantity of water may be needed to carry out the test. Also, the analysis of the test can be quite tedious.

3 THE AIR-ENTRY PERMEAMETER

3.1 Theory

Each technique outlined in Section 2.3 relies upon certain assumptions about the condition of water flow within the soil being tested, such as saturated, isotropic, uniform, vertical and steady-state flow. Some of these assumptions pertain only to particular soils, such as granular and non-stratified soils.

The air-entry permeameter relies upon a principle which is reputed to be unrelated to the nature of the soil. It does, however, assume certain relationships between the saturated permeability, unsaturated permeability, water-entry pressure P_w, and air-entry pressure, P_a. It has been demonstrated empirically[8] that the relationship between permeability and pressure may be simplified to a double step function during negative pressure flow at which point:

$$k_{sat}/k_{unsat} = 2 \qquad \text{and } P_a/P_w = 2$$

This relationship enables an estimation of the coefficient of permeability to be made from a knowledge of the infiltration characteristics, air-entry pressure and flow system dimensions.

The technique involves the infiltration of water at a known head through a cylinder placed within the soil under test. A measurement of the negative pressure required for air to displace water within the pores of the soil and the infiltration rate leads to an estimate of the coefficient of permeability by Darcy's Law.

3.2 Description and method

The air-entry permeameter as described by Bouwer consists of a cylinder of about 0.2m diameter with a sealable transparent lid connected through valves to a supply reservoir, vacuum gauge and air vent.

An excavation is made at the test area to remove the top soil and expose the soil to be tested. The cylinder is driven some 0.1m into the soil under test. A layer of sand is then placed inside the cylinder to protect the soil surface and a metal disk is placed on the sand to break the energy of the water entering the cylinder from the supply. The lid is clamped to the cylinder and connected to the supply reservoir.

The head of water in the reservoir is maintained at a relatively high level, up to 1m, above the cylinder in order to achieve a high hydraulic gradient and correspondingly a reasonable infiltration rate. The cylinder is charged with water by opening the air vent valve and supply valve and maintaining the head in the reservoir. When all of the air is driven from the cylinder the air escape valve is closed and the water from the reservoir is allowed to infiltrate the soil. When the infiltrating "wet-front" is considered to have reached the lower end of the cylinder, the rate of fall of the water level in the reservoir is measured to provide an infiltration rate and the supply valve is then shut, freezing the advance of the wet-front.

Next, a vacuum develops inside the cylinder until eventually the air-entry pressure is reached and air is drawn up under the edge of the cylinder and begins to bubble up inside. The pressure at which this happens is measured by watching for the minimum pressure reading on the vacuum gauge and relating this to the elevation of the wet-front.

The water-entry pressure may be taken as half of the air-entry pressure according to the step function stated in Section 3.1 above. In this way one obtains the infiltration rate (by observing the water level in the reservoir) and the hydraulic gradient (from the average reservoir level related to the water-entry pressure). These can then be used in Darcy's Law to provide the coefficient of permeability.

For the design outlined above:

$$k_{sat} = \frac{2\,dH/dt\ L\ R_r^2/R_c^2}{(H_t + L + P_a/2)}$$

where dH/dt = rate of fall of water level in reservoir just before closing supply valve.

H_t = height above soil surface of water level in reservoir at time supply valve is closed

L = depth of wet-front

R_r = radius of reservoir

R_c = radius of cylinder

4 HR MODIFICATIONS

The air-entry permeameter as constructed at HR is shown in Figure 1. The dimensions of the cylinder are 20cm diameter, 17cm height and the reservoir is 15cm diameter, 15cm height.

The modifications to Bouwer's design were the shaping of the underside of the lid, the use of a mercury manometer for pressure measurement and the use of an electrical conductivity probe for the detection of the wet-front.

The reservoir was connected via extending rigid tubes and was supported on a tripod.

4.1 Shaping of lid

The underside of the cylinder lid was shaped so that the highest point within the cylinder was at the air vent valve.

This was included in the design in order to ease the purging of air from the cylinder. It also minimised the amount of air becoming entrapped in the pressure measuring system.

4.2 Pressure measurement

In Bouwer's original design, a bourdon-type vacuum gauge with memory pointer was used to indicate the minimum pressure that developed. This seemed to present two problems. Firstly, the difficulty in excluding air from the gauge and connecting hose, which may confuse readings; secondly, the cost of a gauge with sufficient accuracy and range.

To overcome this, a mercury-water manometer was constructed and connected via a 3-way valve. With no water in the permeameter, the valve was switched so that the manometer was isolated and the cylinder vented to atmosphere. Once full of water, the permeameter could be connected to the manometer by one turn of the valve.

This method was used during the preliminary trials of the air-entry permeameter. It did however, become apparent that this system was awkward to use in the field. Care had to be taken to ensure that the manometer always remained vertical during use and that it was secure during transportation. Accidental spillage of mercury in the field is highly undesirable. On reflection, it was decided not to incorporate the mercury manometer into the field equipment.

Instead, the manometer was replaced by a differential pressure transducer. This instrument was located on the permeameter lid and measured the difference between the pressure within the cylinder, immediately beneath the lid and atmospheric pressure above the lid. This information was converted to an electrical signal between 0-1 volt over the pressure range for which the transducer was set (+2m to -2m water pressure). The output was measured in volts and converted directly to water gauge pressure using a suitable interface. This method also allowed a continuous chart recording of the pressure evolved during a permeability test, for later scrutiny. Figure 2 shows a chart record of the pressure measured at each stage of a test.

One further advantage of using a pressure transducer is that it also reads the height of water in the reservoir, relative to the transducer position, and monitors the rate of drop in water level in the reservoir for the calculation of hydraulic gradient and infiltration rate. If this information is recorded on an appropriate automatic chart recorder, the operator is free to tend to the running of the test. This equipment can be expensive but is worthwhile if much testing is required.

4.3 Wet-front detection

In order for the theory relating the flow conditions within and around the permeameter to the coefficient of permeability to hold true, the advancing "wet-front" of infiltration must be level with the base of the cylinder at the time that the supply valve is shut. In order to locate the position of this wet-front, HR proposed an electrical conductivity probe inserted in the soil within the cylinder. This is also shown in Figure 1.

The probe originally consisted of two stiff wire electrodes, insulated from each other but bare for about 2mm at the ends and separated from each other by about 2mm. The probe could then be pushed into the soil so that the bare ends were level with the edge of the cylinder. The electrical resistance between the two probes could then be measured using a standard AVO meter. When the wet-front reached the electrodes of the probe, the electrical conductivity would have been expected to increase (resistance would be seen to decrease) and this could be monitored by the AVO meter.

In order to check that the probe really did register the moment when the wet-front in general was at the correct depth, a test was carried out in a perspex-fronted tank. Soil was compacted into this and the probe was pushed in to about 10cm. Water was added and the advancing wet-front was watched. The electrical conductivity was seen to rise rapidly as the water approached the tip of the probe, instilling confidence in the method. The results of this test are presented in Figure 3.

When the probe was tested in the field, however, the detection of the wet-front was less obvious. This was because the soil, although not saturated, had a moisture content that appreciably raised the electrical conductivity of the soil, so there was little difference between the electrical conductivity with and without the presence of the wet-front.

An attempt to rectify this by utilising salt water for the test was considered but although this improved the detection of the wet front, caution was required here. Salt not only increases the electrical conductivity of the test water but also increases its density and viscosity, which can have a bearing on the validity of any permeability calculations. Furthermore, the use of salt water can cause an artificially high degree of swelling of clay minerals which could potentially alter the soil system under test.

A further modification to the probe method was tested by using only one electrode within the probe and utilising the cylinder itself as the second electrode. This method increased the area over which the electrical conductivity was measured. The resulting change in conductivity due to the approaching wet-front, though greater, is less sharp.

In view of the problems and inaccuracies that were discerned using the probe method, it is appropriate to locate the wet-front approximately by the following simple calculation of volumes.

radius of reservoir, $R_r = 7.5cm$
radius of cylinder, $R_c = 10cm$
depth to wet-front, $L = 10cm$
assumed porosity of soil, $\Theta = 0.3$

Therefore, the drop in reservoir level to provide the volume of water required to saturate the soil in the cylinder to depth L

$$= L\,\Theta\,\frac{R_c^2}{R_r^2} = 5cm$$

This drop in level is measured from the time that the air vent valve is shut. Although approximate (it is assumed that no water infiltrates the soil until the cylinder is fully charged and that porosity = 30%), this method has been used in conjunction with the electrical conductivity probe to determine when the supply valve should be shut.

5 FIELD TESTING

5.1 Air-entry permeameter

The air-entry permeameter constructed at HR was used to estimate the coefficient of permeability of River Thames flood plain deposits. Three soils were chosen from the vicinity of HR at Wallingford, Oxfordshire. The soils were well graded river flood plain loams and were labelled 1, 2 and 3 in order of increasing clay content.

Further air-entry permeameter tests were then carried out on a well sorted sand, labelled 4, an artificial soil of expected high permeability. At each location several tests were carried out.

Once the apparatus was set up, the tests were performed easily by one operator and each was completed within one hour.

The tests carried out on soil 3 failed. The initial infiltration rates were unexpectedly high. Furthermore, it did not prove possible to achieve a value for the air-entry pressure. The negative pressure did not evolve far but equalised at a fairly low value.

A hypothesis to explain this, could be as follows. Initially, a high infiltration rate occurred due to the absorption of water into the fissures of the initially fairly dry and structured clay soil. Secondly, once the supply was shut, a low infiltration rate took place due to swelling of the clay soil to form a plug in the cylinder. Finally, equilibrium of pressure became established due to air having time to come out of solution from the highly aerated test water.

5.2 Hazen method

At each location, soil samples were taken and analysed for particle size distributions, as presented in Figure 4. The d_{10} particle sizes have been derived from these analyses, enabling an estimate of the coefficients of permeability to be made according to the Hazen formula.

5.3 Pump-in test

The shallow well pump-in method was carried out by augering a 75mm diameter hole to 1m depth from the base of the top soil at the location of soil 1. The borehole was filled with water and the level was maintained constant for 30 minutes. The water level was then allowed to fall. This fall was monitored by taking regular dip readings on the water level. After 5 hours had passed, the level had only dropped by 0.4m. The borehole was then topped up again and the water level decline was monitored for 1 hour. The rest-water level, 15 hours later, was found to be 0.53m below the top of the borehole and a silt level was found to be at 0.58m below the top of the borehole.

For the analysis of the test, k is derived from the flow rate, Q, due to the head of water, H, from the borehole of radius, r, according to the equation[4]:

$$k = \frac{Q}{2\pi H^2}\left[\ln\left(\frac{H}{r} + \sqrt{\frac{H^2}{r^2} - 1}\right) - 1\right]$$

In this case, though, we believe that an impermeable layer effectively exists at 0.53m below the top of the borehole, because this was the rest level in the hole. This may have been caused by smearing of the clays in the soil during augering or due to fine material sealing the surface layer of soil which had slumped into the hole. The flow dynamics should therefore obey the equation:

$$k = \frac{Q}{\pi H^2} \ln \frac{H}{r}$$

and this was used in the analysis of this test, with H measured as the head above 0.53m depth.

The decline of water level with time during the test is shown in Figure 5. A range of values for k were calculated by using a range of gradients from this graph to obtain H and Q.

5.4 Double tube test

This test was carried out at the location of soil 1 by the method described in Section 2.3.5. The outer tube used was 0.2m diameter and the inner tube was 0.1m diameter. The inner tube was isolated from the outer tube whilst the inner tube water level was allowed to decline and the level in the outer tube was maintained constant. The inner tube was then topped up and a valve was opened to connect the two tubes. The water levels in the two tubes were then allowed to decline simultaneously.

The analysis of the test relies upon the distortion of the flow patterns between the outer tube full condition and the equal levels condition. It has been shown theoretically[7] that:

$$k = \frac{R_c}{F_f} \frac{\Delta H_t}{\int_o^t H dt}$$

where R_c = radius of inner tube

ΔH_t = difference in water levels between the two conditions at time, t.

$\int_o^t H\,dt$ = area under the curve of a graph of water level against time for the outer tube full condition at time, t.

F_f = a flow factor depending upon the size and penetration of the tubes. In this case, $F_f = 1.2$.

The graph of water level against time for the test is presented in Figure 6. It can be seen that the outer tube full condition resulted, virtually, in a straight line but the equal levels condition deviated from a straight line after about 8 minutes, after which the divergence of the lines was no longer constant. In this test, only the data for the first 8 minutes was used for the calculation of k.

6 RESULTS AND DISCUSSION

The results of the air-entry permeameter tests are listed in Table 1. From a knowledge of the soil types, the values of coefficients of permeability that would be expected for soils 1, 2, 3 and 4 are likely to lie within the ranges 10^{-5} to 10^{-4}, 10^{-6} to 10^{-5}, 10^{-7} to 10^{-6} and 10^{-3} to 10^{-2}m/s respectively, though there is no independent verification of these values.

The coefficient of permeability measured for soil 1 was somewhat higher than expected. The infiltration rate measured during these tests was quite high and it is possible that leakage through preferential paths, such as fissures in the structure of the soil, may have occurred. These conditions are unlikely to exist in a fully saturated environment.

Soil 2 provided results which were in the range expected for the soil. The test appeared to work well.

As discussed in Section 5.1, no results were obtained for the clay comprising soil 3.

The results of the test on the sand comprising soil 4 are high but not unreasonable considering the loose condition of the soil. Again, the test appeared to work well.

The results of the air-entry permeameter tests are listed in Table 2 with the coefficients of permeability derived according to the Hazen formula for comparison, and also the pump-in and double tube tests for soil 1.

The values of k, according to Hazen, for soils 1, 2 and 3 appear to be rather low. This is a reflection of the clay content within the loams. The formula method has over-estimated the effect of the finer 10% of the soil on the overall permeability.

The value of k by Hazen for soil 4 is considered to be an under-estimate. The formula does not take into account the loose condition of the sand.

The results of the pump-in test are on the low side of the range expected. Due to the difficulties experienced during the test and the corresponding uncertainty in the calculation, little faith can be put in the result of this test.

The double tube test provided a result within the range expected. This test appeared to work well in this case.

7 CONCLUSIONS AND RECOMMENDATIONS

In order to assess the potential for failure of river flood embankment schemes due to short-circuiting by groundwater flow, it is necessary to estimate the permeability of the soils that govern the hydrogeology of the flood plain. The top layers of these soils typically consist of well graded loam deposits and their in-situ permeability is a notoriously difficult quantity to measure.

The air-entry permeameter is a device which is generally suitable for the in-situ measurement of the Darcy coefficient of permeability of a soil above the water table. The method obviates many of the inconsistencies of other small-scale testing methods.

It is not possible, however, to be conclusive about the accuracy of the results obtained because there is no reliable independent verification of the true permeability values. We can only comment on the sensibility of the results. In the tests carried out, it was found that the procedure worked satisfactorily with the exception of the test on the most clayey soil as discussed in Section 5.1 above.

Careful measurement of pressure is required. Continuous monitoring of pressure on a chart record is recommended.

The total cost of equipment and construction of the permeameter used at HR was in the order of £2,000.

An engineer faced with the problem of calculating groundwater flows in the vicinity of proposed flood embankments may use equipment such as the air-entry permeameter to obtain estimates of the coefficient of permeability of the loams. This data may then be used to construct a model of groundwater flow. Later, the permeability values may need to be modified slightly in order to take into account any discrepancies that become evident during the calibration of the model to measured prototype conditions. However, should the first estimates of permeability be grossly inaccurate, the model may contain intrinsic errors that cannot be rectified without a complete re-evaluation of the hydrogeologic system envisaged. It is, therefore, imperative that hydraulic parameters such as the coefficient of permeability are estimated with the greatest possible confidence.

All methods of permeability testing of soils are liable to reflect large variations. The smaller the scale of the test, the less representative the result due to natural variability of the soil. The use of a larger cylinder, say 0.5m diameter, may provide more representative results by testing a larger area of soil, though a correspondingly larger quantity of water would then be required. It may also prove that the cylinder would need to be weighted down to counteract the upward hydrostatic pressure during infiltration and this may create inaccuracies due to compression of the soil. Generally, the higher the permeability and the greater the uniformity of a soil, the easier and more confidently permeability can be measured. It is important to choose a test that is suitable for the type of soil being tested and at a scale indicative of the accuracy required and cost effectiveness achievable.

Work to be carried out by HR during 1987-1988 under this MAFF research agreement will involve a consideration of the modelling and calculation techniques which may be applied to engineering problems concerning the flow of groundwater beneath flood embankments.

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TABLES.

TABLE 1: **Results of air-entry permeameter tests**

Soil	Description	Infiltration rate (mm/s)	Air-entry pressure (m.WG)	Coefficient of permeability (m/s)
1	Loam	0.37 - 0.73	0.21 - 0.29	$5x10^{-3}$ - $9x10^{-3}$
2	Loam	0.11 - 0.20	0.18 - 0.195	$2x10^{-5}$ - $4x10^{-5}$
3	Loam	1.25 - 1.75	> 0.17	-
4	Loose sand	0.9 - 5.0	0.38 - 0.39	$1.5x10^{-2}$ - $8x10^{-2}$

TABLE 2: **Comparison of results from permeability tests**

	Coefficient of permeability, k, (m/s)				
Soil	from inspection (guesswork)	air-entry	Hazen	Pump in	Double tube
1	10^{-5} - 10^{-4}	$5x10^{-3}$ - $9x10^{-3}$	$2x10^{-7}$	$1x10^{-6}$ - $1.5x10^{-5}$	$8x10^{-5}$
2	10^{-6} - 10^{-5}	$2x10^{-5}$ - $4x10^{-5}$	$4x10^{-8}$		
3	10^{-7} - 10^{-6}	-	$1x10^{-8}$		
4	10^{-3} - 10^{-2}	$1.5x10^{-2}$ - $8x10^{-2}$	$1.4x10^{-4}$		

FIGURES.

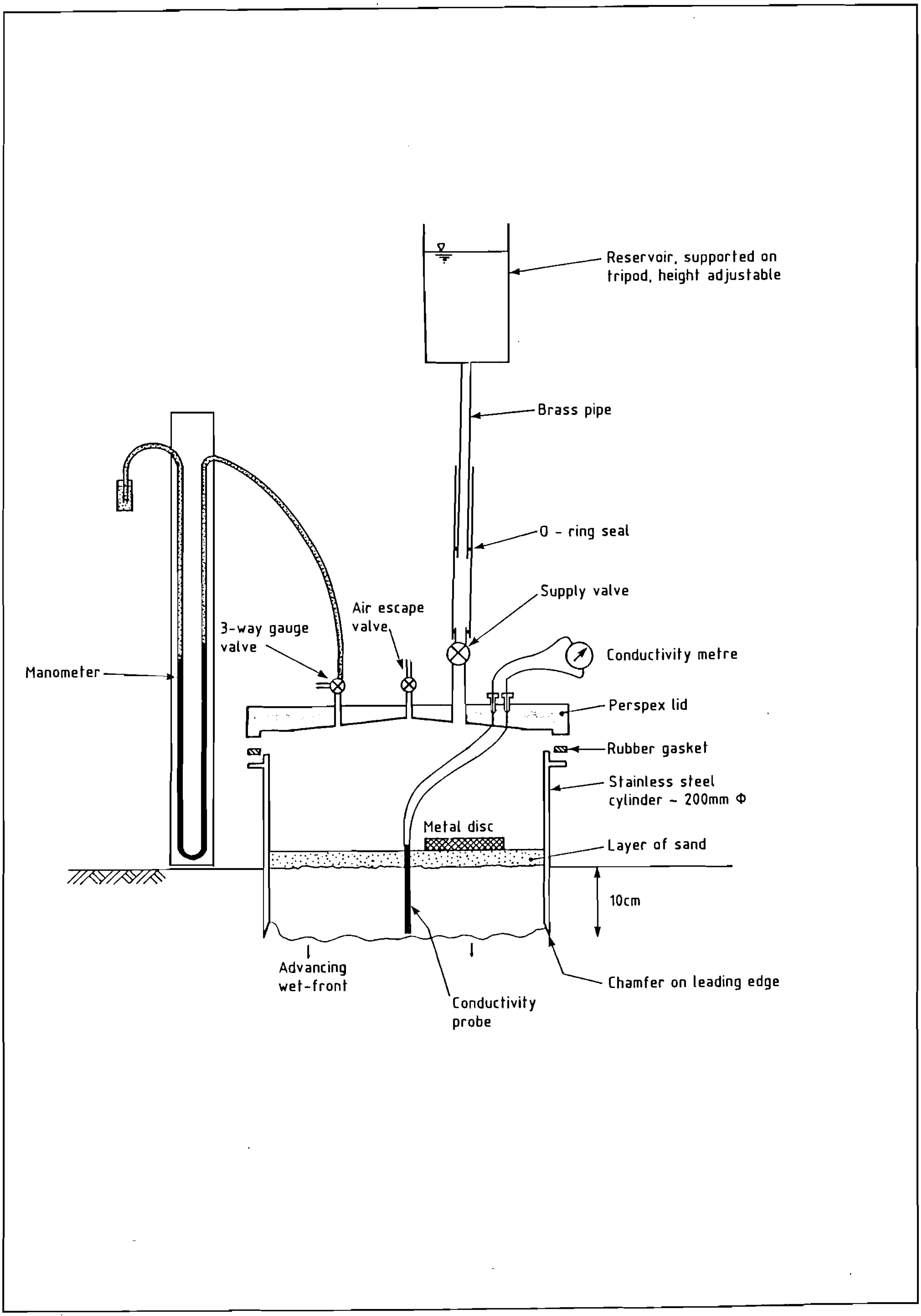

Fig 1 Diagrammatic representation of air-entry permeameter

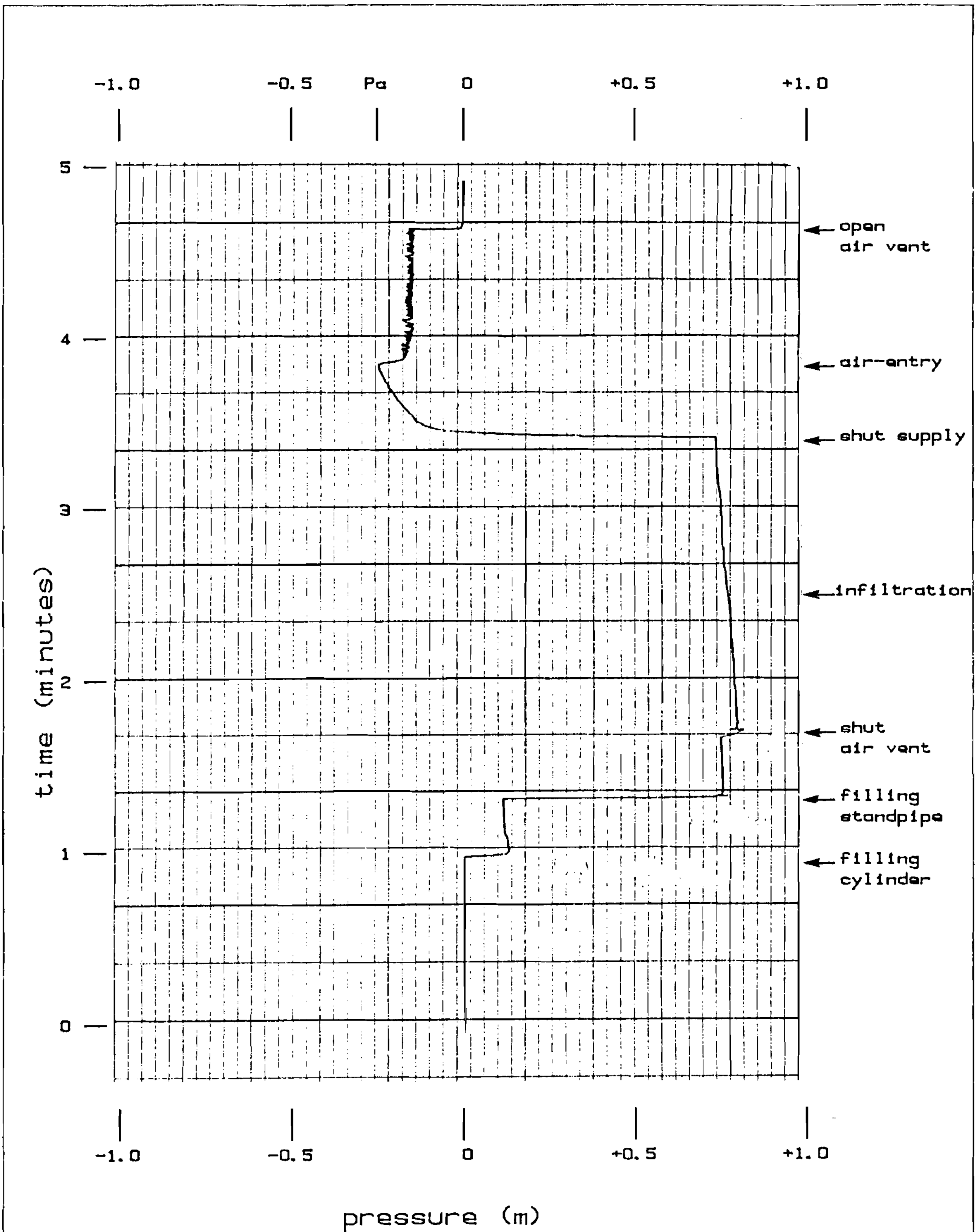

Fig 2 Pressure recorded during air-entry permeameter test

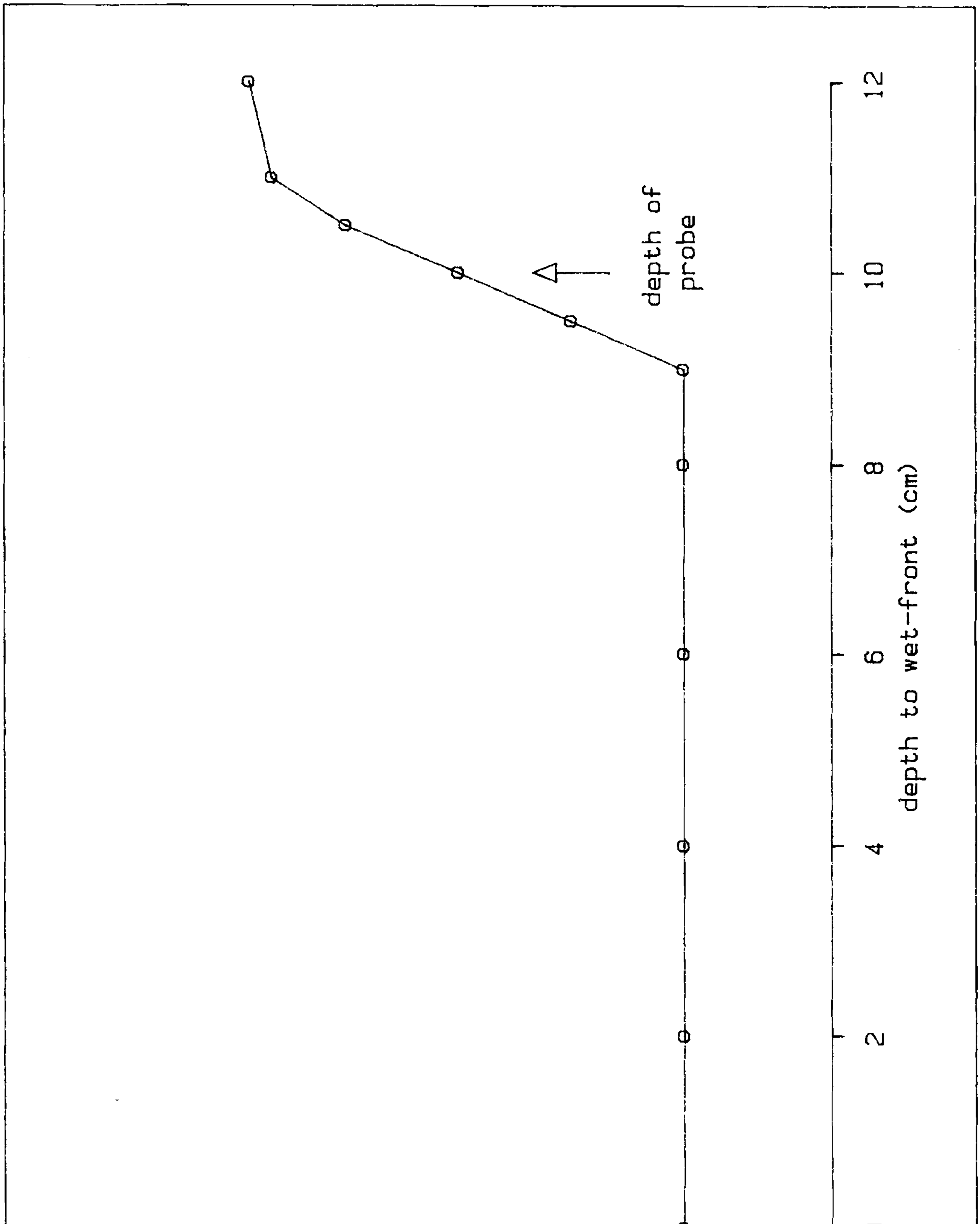

Fig 3 Current measured by probe during laboratory test

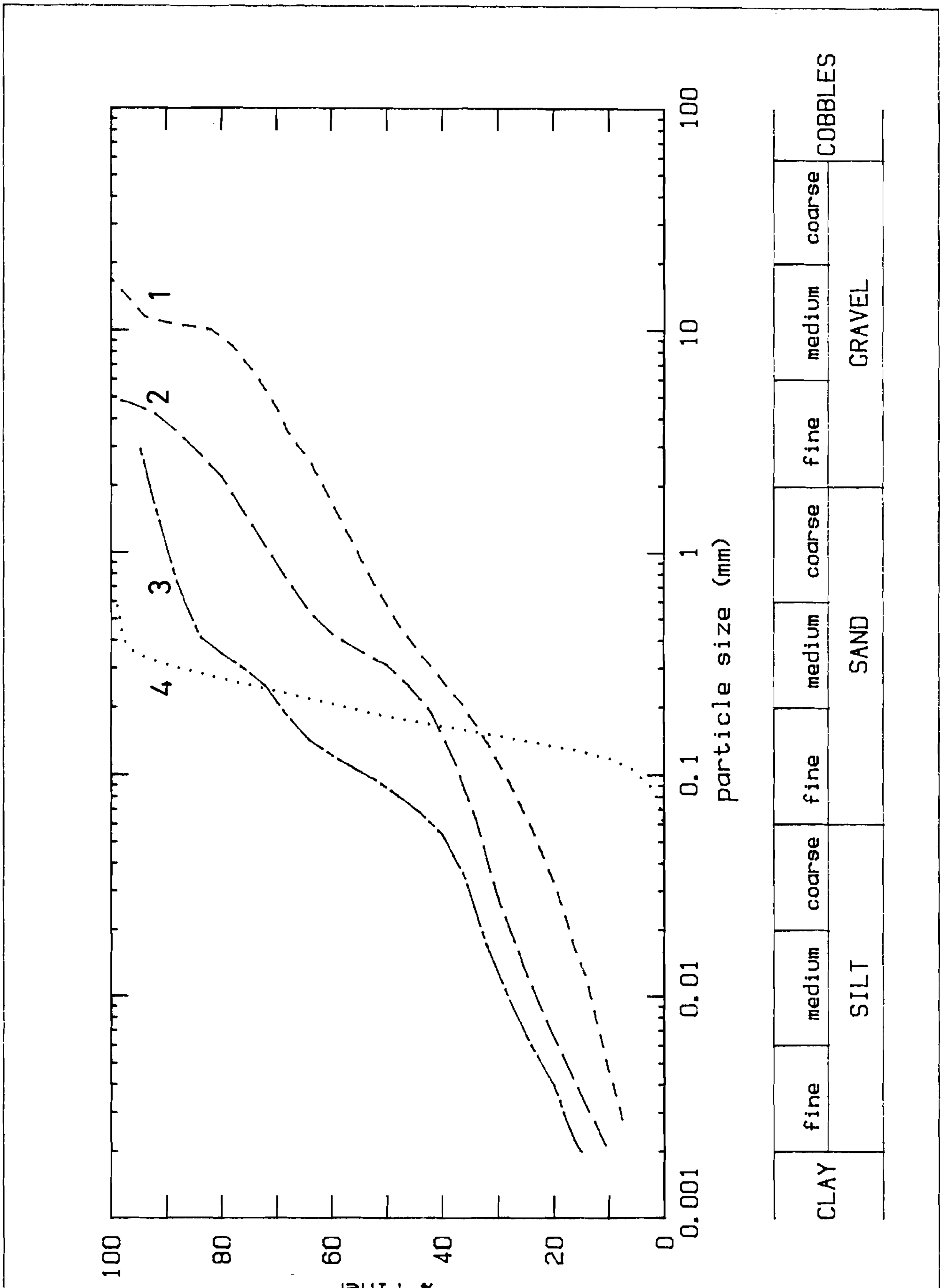

Fig 4 Particle size distributions of soils 1 2 3 and 4

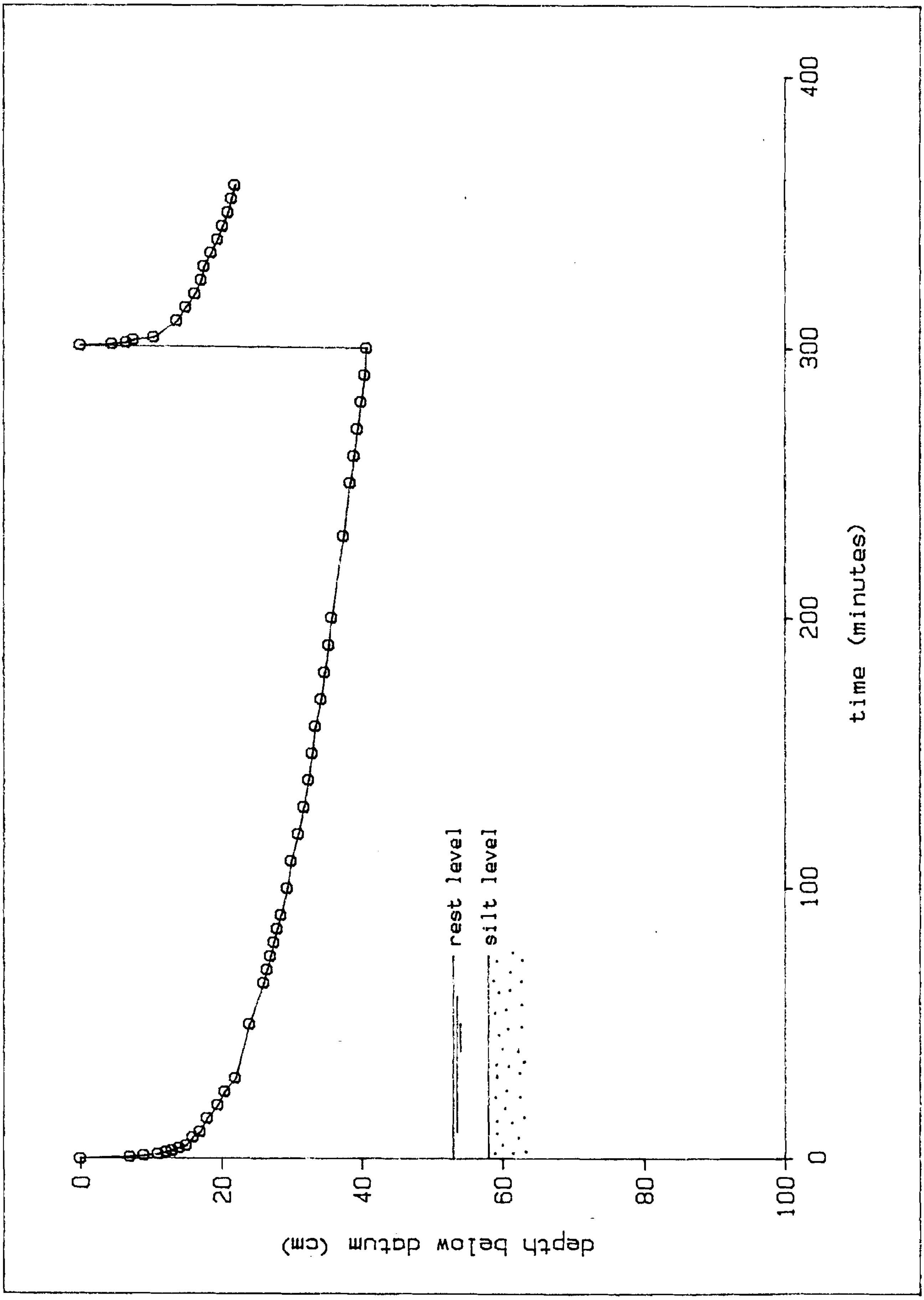

Fig 5 Analysis of pump-in test

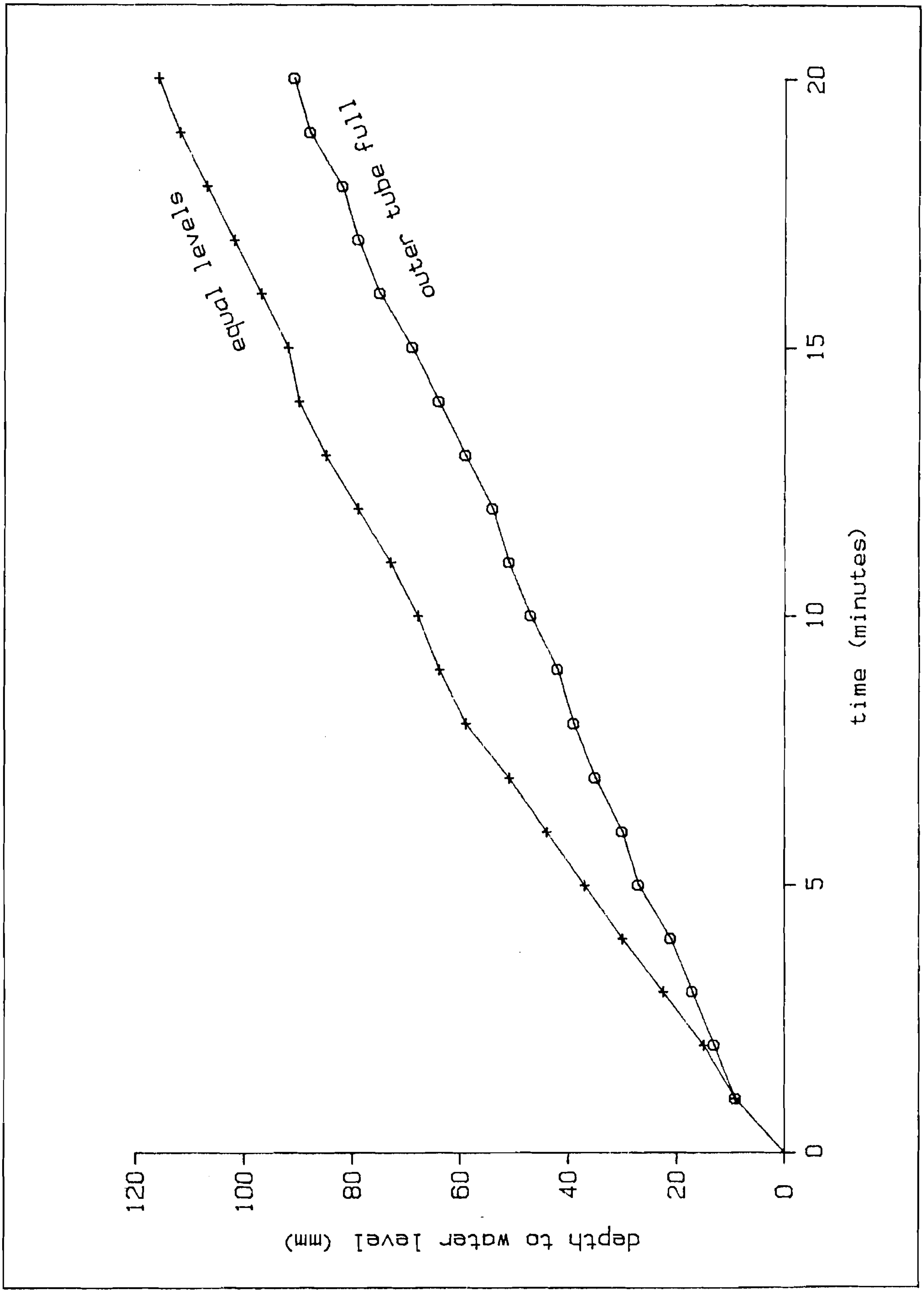

Fig 6 Analysis of double tube test