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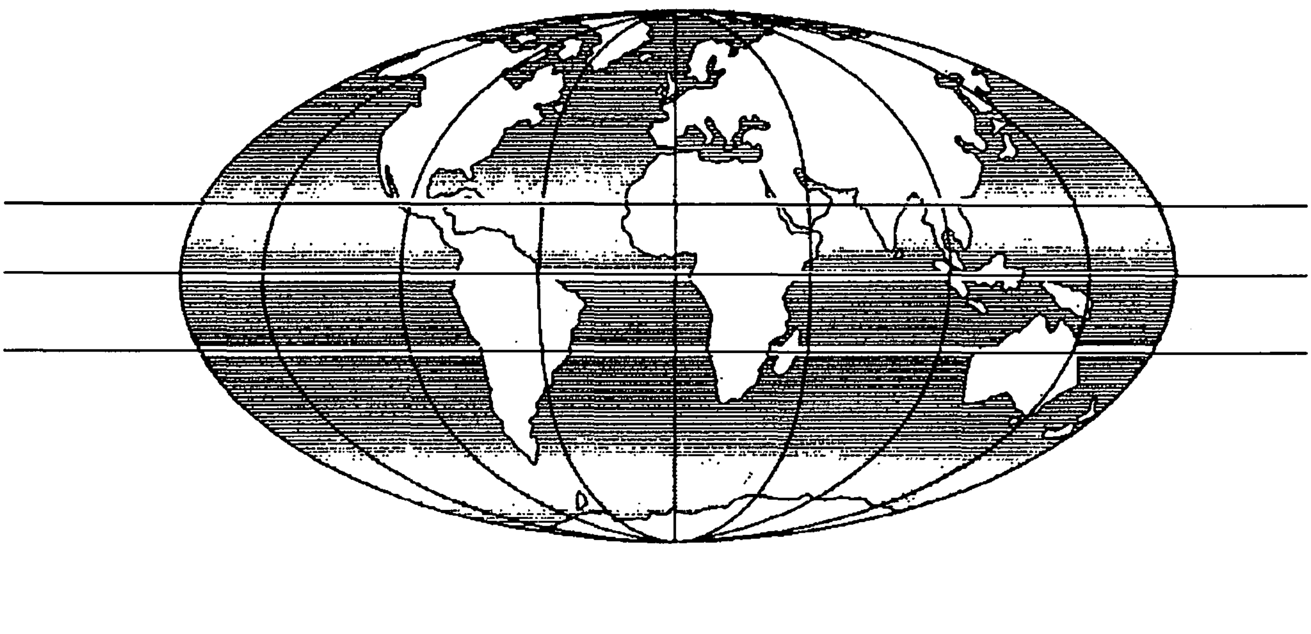
TITLE A simple field suction measurement probe

by M S Crilly, H D Schreiner and C S Gourley



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A simple field suction measurement probe

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ABSTRACT. Few successful attempts have been made to measure pore water suctions in unsaturated soils over long periods in the field. Failures have frequently occurred due to calibration changes of the probe, as happens with the gypsum block, and due to mechanical damage, to psychrometer probes for instance. Since the suction is a major factor in the strength, swell and collapse of unsaturated soils, its measurement is of great importance. This paper describes a new field probe, based on the filter paper technique of suction measurement. Three prototype installations in the UK and two road monitoring installations in Kenya are described. The results show that this relatively simple device is reliable and sufficiently accurate for general use.

1 INTRODUCTION

The filter paper technique of measuring suctions in soil samples was first introduced by Gardner (1937) for use in the field of soil science. The technique involves placing a piece of filter paper in contact with, or close to, a soil sample until the water content of the filter paper is in equilibrium with the soil suction.

If the filter paper is in contact with the soil then the suction measured is the matrix suction, since the soil water and the filter paper water will be identical and there will be no osmotic effects. However, if there is no contact between the filter paper and the soil, the measured suction will be the total suction, since the water in the filter paper will effectively be distilled water.

Fawcett & Collis-George (1967) performed calibrations on Whatman's No 42 filter paper treated with 0.005% $HgCl_2$ solution to avoid fungal and bacterial growth. Hamblin (1981) repeated these correlations with both treated and untreated papers, and reported that treatment did not affect the correlations. The correlations were again repeated by Chandler & Gutierrez (1986) who found good agreement between their data and the earlier data in the suction range 80 kPa to 6000 kPa, indicating a high degree of repeatability across both time and manufacturing lots. They suggest that, in this range, the filter paper water content, w %, in equilibrium with a soil suction, −u kPa, is given by

$$-u = 9.81 \times 10^{(3.85 - 0.0622w)} \qquad -(1).$$

The filter paper technique works well as a wide ranging method of measuring matrix and total suctions in the laboratory. However, until now, it has not been used as a field technique.

There are a number of existing field suction measurement techniques such as tensiometers, gypsum blocks and field psychrometers, none of which is entirely satisfactory as a measurement technique.

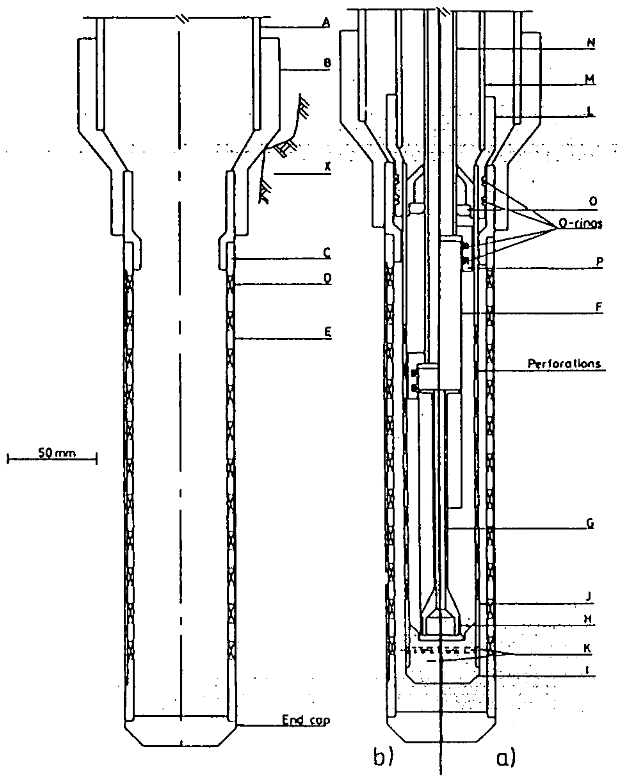
Psychrometers, which are probably the most commonly used of field suction measurement devices, are not particularly robust, and problems with corrosion are often encountered. In addition, they tend to be rather inaccurate at low suctions.

It was therefore considered that a field system based on the filter paper technique could considerably improve upon existing field suction measurement systems.

2 DESIGN

In order to develop a new field suction measurement system, the following points were considered to be central to the design:

- the system should have a cheap, disposable sensor (ie filter paper) to avoid problems of reliability



Figs 1 & 2. Filter paper suction probe: outer borehole lining; outer lining and inner assembly, a) open, b) closed.

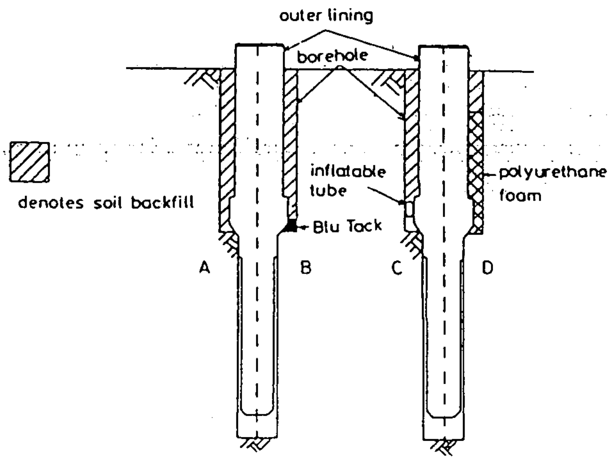


Fig 3. Four possible sealing techniques.

• the system should be simple, both to install and to operate, using, as far as possible, off-the-shelf components

• Chandler & Gutierrez (1986) found that, under laboratory conditions, wet filter paper dries out at a rate of approximately 1 %/min. The filter paper cell should therefore be sealed within the sensing chamber to avoid moisture loss

• to avoid excessive temperature changes, there should be minimum heat conduction from the ground surface to the sensing point.

For these reasons, it was decided to base the design on commercially available sizes of PVC piping, chosen to fit around a flat-bottomed glass test tube with a polythene lid, containing the filter paper. In addition, it was decided to use a no contact technique because of the difficulty involved in obtaining good contact between a piece of filter paper and an exposed soil face at the foot of a borehole and the subsequent uncertainty as to whether total or matrix suctions were being measured: thus, total suctions will always be measured. The design adopted is shown in Fig 1, which shows the outer borehole lining, and Figs 2 a & b, which show the inner assembly in both open and closed positions.

The outer lining, Fig 1, comprises a length of plain pipe, A, fitting into a reducing socket, B, which in turn fits onto a smaller diameter pipe, C, perforated, D, over most of its length and wrapped with a fine stainless steel mesh, E. This outer lining forms the permanent borehole lining, the suction being measured over the perforated length. The stainless steel mesh serves to keep the measurement chamber clean.

At the centre of the inner assembly, Fig 2, is the test tube, F, which contains the filter paper, wrapped around an aluminium guide rod, G, and held by a small o-ring. The test tube cap, H, is held by a removable end cap, I, secured to a perforated pipe, J, by two brass pins, K. This perforated pipe fits into a reducing socket, L, which has been modified by cutting two o-ring grooves around the smaller diameter section, which in turn fits into a larger diameter plain pipe, M. This plain pipe is used to position the inner assembly in the outer lining. The glass tube is raised and lowered by means of a small diameter pipe, N, which runs through a shaft seal and guide, O, and is connected to a socket containing two o-rings, P, which hold the test tube in place.

To operate the device, the inner assembly is lowered into the borehole lining and a seal is formed between the o-rings on the inner assembly and the inner wall of the reduced section of the borehole lining. The test tube is held open while the filter paper is equilibrating (Fig 2a). When the inner assembly is ready to be removed, the test tube is closed by pushing on the plunger (Fig 2b).

A good seal between the collar of the outer lining and the soil, X in Fig 1, is crucial to the operation of the device.

Four different sealing techniques were investigated (Fig 3):

- no additional materials - the outer lining simply being hammered into place
- an approximately 5-8 mm thick collar of Blu Tack placed around the reducing socket and spread against the soil by hammering on the top of the lining
- an inflatable tube around the reducer
- a setting polyurethane foam between the lining and the soil.

It was found that, with the exception of the plain casing, all of the other techniques gave good seals. Blu Tack was therefore adopted as the simplest and cheapest sealing method.

3 INSTALLATION PROCEDURE

A number of prototype devices have been installed at various sites in the UK and Kenya. Most of these devices were installed by the procedure described below:

- auger a 150 mm diameter hole to the top of the measurement position
- progress this hole a further 400 mm at a smaller diameter by driving a 75 mm sample tube
- clean out the hole using an industrial vacuum cleaner
- assemble the outer lining, placing a collar of Blu Tack on the reducer
- place the lining in the hole, and seat it with a few light drops of a sledge hammer
- backfill around the lining with excavated material, compacting it with a 25 mm diameter steel rammer.

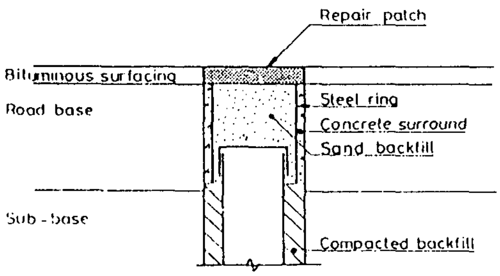


Fig 4. Cover arrangment used under a surfaced road in Kenya.

The cover detail depends on the ground cover, and should therefore be designed for each situation. Fig 4 shows an example of an arrangement used under a surfaced road in Kenya. The use of a road repair patch camouflages the instrument as a routine road repair and avoids the likelihood of unauthorised access which might occur via a visible steel capping.

4 MEASUREMENTS

All of the results described below were obtained by the following procedure for measuring the filter paper water content. At the end of each equilibration period, the test tube containing the filter paper, aluminium rod and the o-ring was closed and then removed. The outside of the closed test tube was next cleaned with butanone and then the test tube, complete with cap, o-ring, aluminium rod and filter paper was weighed. The test tube was then opened and the test tube and wet filter paper placed in an oven at 100-110°C for several hours while the test tube cap, aluminium rod and o-ring were allowed to air dry in the laboratory atmosphere. Duran (1986) found that there were no consistent variations in water contents after 1 hour and 24 hours of drying. The aluminium rod was weighed separately and then the test tube and dry filter paper removed from the oven, the cap replaced, putting the o-ring back into the test tube, and weighed. All weighings were carried out on a balance which is graduated in 0.0005g increments and can be read to 0.0001g. The dry mass of the filter paper and the filter paper water content were then calculated.

5 RESULTS

5.1 Laboratory prototypes

Three prototype devices were installed in a tank in a temperature controlled (20±1 °C) laboratory. Black Cotton Soil, a highly plastic clay, at an average water content of 29 %, or about 10 % below British Standard 2.5 kg rammer optimum water content, was compacted around the outer linings up to the collar. These devices were used initially to demonstrate the feasibility of the technique and to investigate the response time of the filter paper in this configuration.

125mm diameter Whatman's no 42 filter paper was used with the edges of the paper trimmed to suit the length of the aluminium rod. In these tests, aimed at establishing the equilibration time, a single piece of filter paper was used in device no 2, while two pieces of filter paper were used in devices 1 and 3. Filter papers were installed for periods of 1, 2, 4, 7, and 28 days.

The results from these tests are shown as the filter paper water content against time in Fig 5. From this graph, it can be seen that both the device with one paper and those with two papers come to an effective maximum water content after an

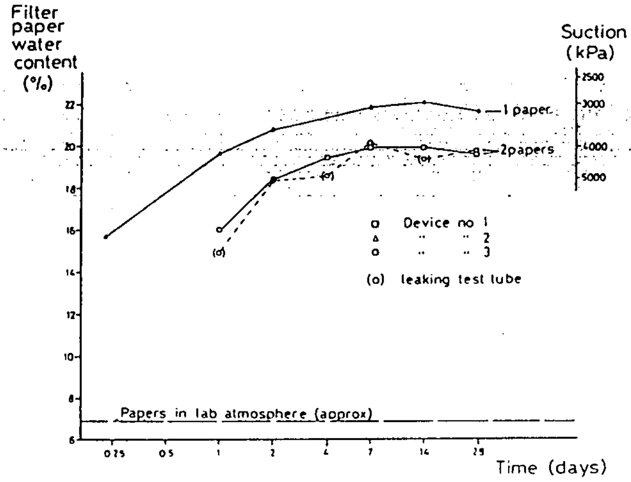


Fig 5. Filter paper water content against eqilibration time for laboratory devices.

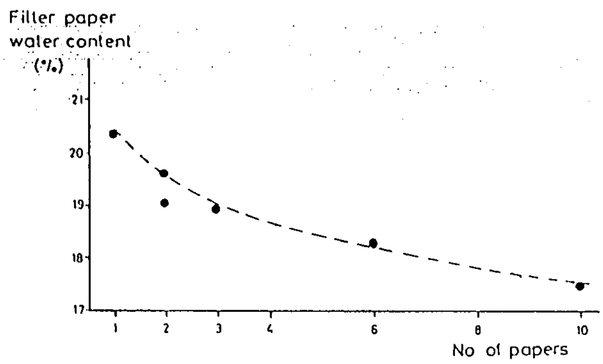


Fig 6. Variation of equilibrium water content with no of filter papers for laboratory devices.

equilibration period of around one or two weeks, though it appears that the equilibrium filter paper water contents differ depending on the number of papers. The device with a single filter paper has an equilibrium water content of 21.8%, while the devices with two filter papers have an equilibrium water content of 19.8%, corresponding to suctions, using equation (1), of 3060kPa and 4070kPa respectively.

Further tests were carried out using 3, 6, and 10 papers, the results of which are shown in Fig 6. It can be seen that as the number of papers increases the filter paper water content decreases. In addition, one test was carried out in a pressure plate, in which three filter paper rolls, made up of 1, 2 and 3 papers, were allowed to equilibrate over a high air entry porous stone, saturated with distilled water, for a period of two months. An elevated air pressure of 300kPa was applied inside the pressure plate, effectively applying a 300kPa suction. At the end of the two month

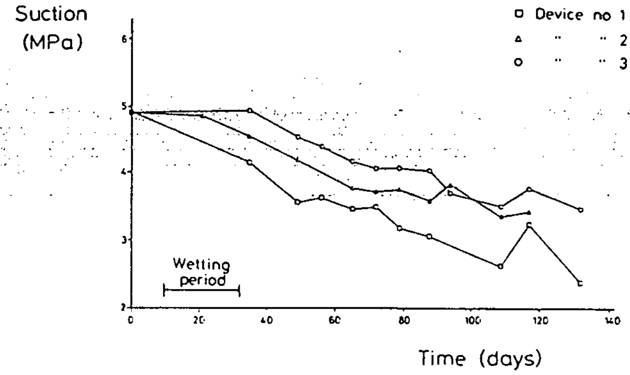


Fig 7. Variation of suction with time for laboratory devices.

period, the water contents of the 1, 2 and 3 filter paper rolls were 37.75%, 36.36% and 35.72% respectively, corresponding to suctions from equation (1) of 310kPa, 380kPa and 420kPa. It would appear therefore that different calibrations are required for different numbers of filter papers.

Schreiner (1988) measured suctions in the same Black Cotton Soil. He also used the filter paper technique, but in such a way as would tend to dry the soil out, and therefore increase the suction in the sample. He measured suctions at various soil water contents, and one test was carried out at virtually the same water content as the soil used to fill the tank. For this test he measured a total suction of 5260 kPa. This can be compared with the suctions inferred above from the filter paper devices where values of 3060 kPa and 4070 kPa were obtained, depending on whether results from the devices with one paper or the device with two papers are used. The fact that the filter paper water contents obtained from the devices are close to but higher than those obtained by Schreiner indicates that the results obtained are reasonable and, particularly, that the mechanical seals do not leak noticeably.

After the equilibration time and the effect of the number of papers had been established, it was decided to increase the soil water content. Enough distilled water was added over a period of 17 days to the tank to bring the overall water content to around 34 %. The tank is approximately 0.77 m diameter with a soil depth of about 0.4 m, and the water was added over the full depth of the soil at four evenly spaced plan locations. The results obtained from the devices, which were monitored in general every 7-10 days using 2 filter papers each time, are shown as suction against time in Fig 7. It can be seen that even in such a small tank, there is still a downward trend of suction with time and a considerable difference between the three devices 100 days after the end of water addition. This gives some indication of the extremely low unsaturated permeability of the Black Cotton Soil.

5.2 Field prototypes

Four devices were installed in March 1989 on an experimental site in Kent, UK. The site is on very plastic London Clay. One half of the site is grass covered, and the other half covered with mature trees, predominantly Poplars. There was no control of the suction on this site except natural climatic events interacting with the vegetation.

The devices were installed in pairs on the site: one pair in the grassed area (C1 & C2); and one pair in the treed area (T1 & T2).

Measured suctions using equation (1) for probes C1, C2, T1 & T2 are shown in Fig 8 against time after the installation of the borehole lining, together with the results of some psychrometer measurements from probe T2. The first measurements were made after a 1 week equilibration period. Results from the test pit installation, described in section 5.3 below, show that this period is too short, and that the water contents will thus be too low and the calculated suction correspondingly too high.

The data show that the suction from probe T1 near the trees is considerably higher than the suction beneath the grassed area measured in C1. Also, the results from the psychrometer in T2 compare reasonably well with those from the filter paper in the nearby probe T1.

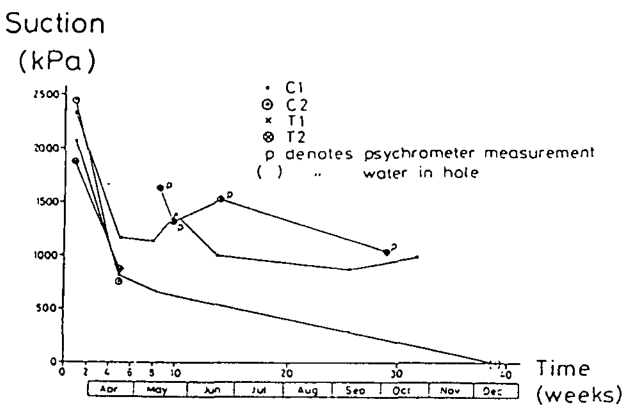


Fig 8. Variation of suction with time for field prototype devices.

5.3 Test Pit Installations

A further eight devices were installed in a test pit inside a hangar at the TRRL, to test the various sealing techniques in Fig 3 for suitability in tropical climates.

The test pit measured 3.0 m by 4.0 m in plan and was divided lengthways into two halves. Each half was lined with polythene sheet and filled with London Clay, compacted in 100 mm layers, to a depth of 1.0 m. One half of the pit was filled with clay at around its natural water content, while the material for the other half had been allowed to dry out considerably before placing. Water content samples taken during compaction gave average water contents of 24 % and 18 % for the wet and dry sides respectively.

Four devices were installed in each side of the pit. It was originally intended to have four pairs of devices, each pair having one of the four different sealing techniques described, so that the efficiency of each technique could be evaluated under different conditions. However, the polyurethane foam was found to be potentially dangerous and was only used for device D4: for device W4 the space between the outer lining and the borehole was filled with compacted fine sand. The remainder of the devices were installed using the arrangements shown in Fig 3. The plan layout of the test pit is shown in Fig 9.

After installation of the devices, readings were taken every week for a period of five weeks. However, it was found that the results were very scattered, and so the equilibration period was lengthened, and readings were taken approximately every two weeks over a further period of 27 weeks.

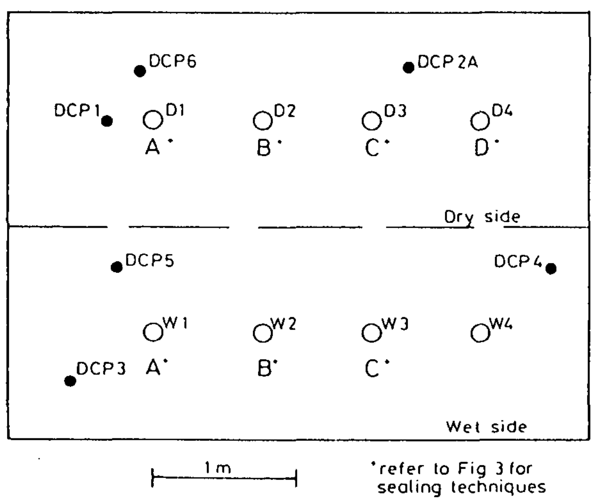


Fig 9. Test pit layout.

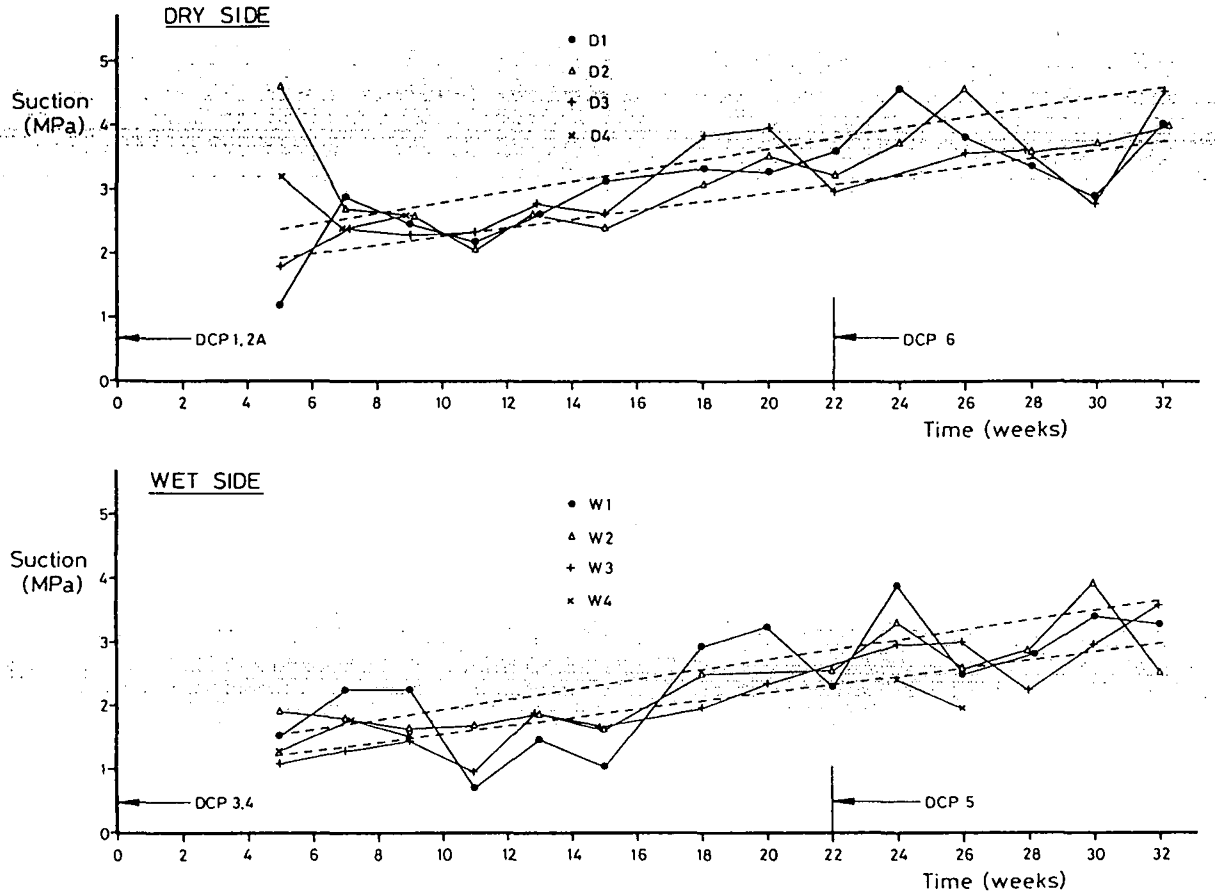


Fig 10. Variation of suction with time for test pit devices.

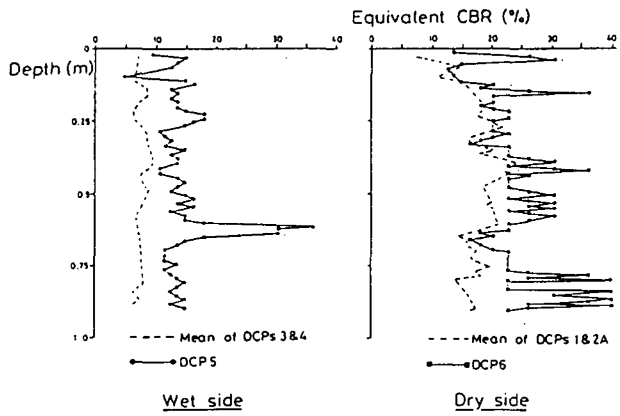


Fig 11. DCP test results from test pit.

The results obtained are shown as suction against time for both wet and dry sides in Fig 10. The readings with one week equilibration periods have been omitted for clarity.

With the exception, perhaps, of W1, the measured suction values are generally within a small scatter. The dashed lines show a trend of overall drying, which initially caused some concern, as the test pit was covered with a plastic sheet. The validity of the suction measurements was checked by performing dynamic cone penetrometer tests (DCPs 5 & 6) in week 22. DCP tests (DCPs 1, 2A, 3 & 4) had been performed to depths of approximately 0.9 m below ground level at the end of compaction (week 0). The locations of the tests are shown in Fig 9.

Fig 11 shows the results of the DCP tests as separate plots for the wet and dry sides. A correlation given by Kleyn & Van Heerden (1983) was used to convert the DCP data to equivalent California Bearing Ratios (CBRs). For both sides, the two original DCP tests gave similar results and so have been shown as a mean line. It can be seen that, on the wet side, there is an increase in mean CBR from about 7 to about 14, while on the dry side, there is an increase from about 18 to about 24. These increases in strength confirm that the observed increases in suction had occurred.

Taking the dashed lines in Fig 10 as a nominal confidence band, the nominal error range is about ±10 % of the mean value.

5.4 Field trials in Kenya

Full scale field evaluation of the probes is being carried out at three sites in Kenya. The sites were chosen to have highly plastic subgrades and climates varying from arid to seasonally wet.

The driest site is trial at km 33+860 on the new Lodwar to Kakuma road. This site forms part of the TRRL dry compaction research which is being undertaken in Kenya and Sudan. Average annual rainfall is about 200 mm. Ten probes were installed.

The intermediate climate site is on the new Garsen Causeway across the Tana river floodplain. Rainfall is about 600 mm per year, but, in addition, it is possible for floodwaters to inundate the lower parts of the embankment. Fifteen probes were installed.

The wettest site is at km 68 on the Nairobi to Mombasa road. This site was previously used as a trial section by TRRL (Jones, 1968). The road has subsequently been reconstructed with subbase, base and surfacing over the original structure. Fifteen probes were installed.

At each site, at least one probe is installed in the open ground remote from the road. These probes will indicate the range of suction due to climate and vegetation. The probes beneath and near the road will reflect the changed conditions due to the sealed surface, the removal of vegetation and any increase in infiltration at the edge of the surfacing.

Preliminary data is available from sites 1 and 3.

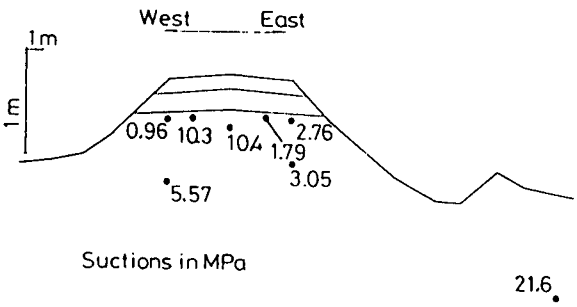


Fig 12. Measured suctions from the Lodwar site.

5.4.1 Lodwar site

The first set of data, collected on 6 March 1990, for the Lodwar site is shown in Fig 12. The measured values range from 0.9 MPa beneath the west edge of the surfacing to 21 MPa in the remote probe to the east of the road. Two glass tubes were broken on removal, and values were not obtained for these points. High values of suction are evident in the middle portion of the road and moderately high values at depth beneath the edge of the surfacing. Data available from the dry compaction research had indicated a zone of raised water content beneath the edge of the road. It is assumed that this is due to infiltration of runoff. The current study of suction in the soil confirms the raised water content zone. The high values of suction closer to the road centre-line indicate that the wet zone has not extended laterally across the whole road, though they are lower than the open field value. However, the value of 1.79 MPa on the east side suggests that the wet zone may be reaching the outer wheel track. It is as yet a high value when compared with the 'design' suction if the road design is based on the soaked CBR value, and suggests that considerable savings in cost may be achievable by utilising the real strength of the subgrade in the design in preference to the soaked CBR value.

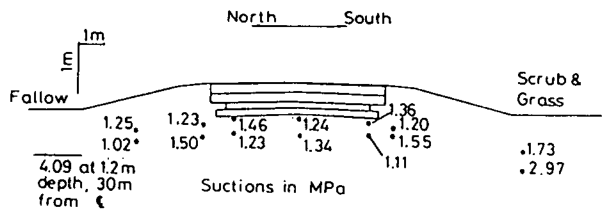


Fig 13. Measured suctions from the Nairobi – Mombasa road site.

5.4.2 Nairobi – Mombasa road site

The first set of data for site 3 is shown in Fig 13. The measured values, obtained near the end of a dry season, range from 1 MPa to 4 MPa. Beneath the road and the shoulders the range is much smaller, being 1.2 MPa to 1.55 MPa. This is consistent with the relatively uniform water contents which were determined from samples taken during probe installations. Lower, water contents were determined on samples taken from the holes to the south of the road and from the hole for the remote probe to the north of the road where higher suction values were obtained.

Measurements made in the laboratory (Schreiner & Burland, 1991; Schreiner, 1988) of the total suction of freshly compacted samples of the same soil at a water content of 34 % gave values of about 4 MPa. Measured matrix suction values of 900 kPa to 940 kPa were obtained from similar freshly compacted samples using a pressure plate cell. Comparison of the laboratory and field results suggest that there has been a considerable change in the pore water pressure during the life of the road and that its foundation is now weaker than it was when built. More data over longer periods would be required to examine this hypothesis.

It is possible that the values of suction will decrease during the wet season. The soil near the edge of the road is likely to show a greater change than the soil beneath the centre-line.

6 CONCLUSIONS

A new device for the field measurement of soil suction has been developed, based on the filter paper technique. The device is mechanically simple and does not require an external power source. It is therefore ideally suited for remote sites in developing countries.

The device has been found to perform adequately. However, there are a number of areas where further work would prove beneficial:

- the filter paper requires recalibration for the number and arrangement of papers being used
- from some preliminary work, it would appear that the filter paper calibration changes slightly with temperature – recalibration is therefore required for a range of possible ground temperatures
- at present, the probe has a relatively large diameter, and it is considered that by making a smaller diameter probe the equilibrium time could be shortened, and the overall cost of the probe reduced.

At the time of writing, a major calibration exercise was underway at the TRRL, while a smaller diameter system was being designed for use under a trial embankment in Kenya.

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