Rapid Field Measurement of Air Entry Value and Hydraulic Conductivity of Soil as Significant Parameters in Flow System Analysis

HERMAN BOUWER

U. S. Water Conservation Laboratory
U. S. Department of Agriculture, Phoenix, Arizona

Abstract. Field measurements of air entry value and hydraulic conductivity of soil are obtained with a covered cylinder infiltrometer equipped with standpipe and vacuum gage. Tests are normally completed in approximately 30 minutes. The resulting data are used to construct step functions relating hydraulic conductivity to (negative) soil water pressure for sorption and desorption. These functions may be used as simplified hydraulic conductivity characteristics to include negative-pressure flow in the analysis of subsurface water movement. Several field and laboratory studies demonstrate the validity of the concepts and the techniques. (Key words: Hydrologic systems; instruments; permeability)

INTRODUCTION

Flow at relatively small negative pressures of soil water, but at essentially saturated hydraulic conductivity, frequently occurs in underground flow systems of importance in hydrology, water engineering, and similar disciplines. Subsurface run-off, for example, may occur entirely as negative-pressure flow. Flow in the capillary fringe above the water table can be significant in subsurface drainage, subsaturation, seepage from canals or through dams and dikes, and in similar systems of predominantly horizontal flow. Downward negative-pressure flow occurs in connection with seepage from open channels to deep water tables or free-draining layers, ground-water recharge or waste disposal with surface basins, infiltration from irrigation furrows or cylinder infiltrometers, etc.

To include negative-pressure flow in the analysis of subsurface flow systems, the relationship between the hydraulic conductivity $K$, and the pressure head of the soil water $P$, relative to atmospheric pressure, must be taken into account. Such curves, which tend to be sigmoid (Figure 1), must be experimentally determined for the soil or soils in question. The procedures are relatively tedious, and representative curves are difficult to obtain [Bouwer, 1964, and references therein]. Moreover, use of a given $K$-$P$ curve in the analysis of flow systems requires iterative procedures using a resistance network analog [Bouwer, 1959] or a digital computer [Reisenauer, 1963].

Inclusion of flow at negative pressures in the analysis of flow systems with the foregoing approach yields a higher flow rate than when this flow is neglected. The same increase in flow rate can also be obtained if the flow system is solved on the basis of saturated hydraulic conductivity for the entire system but with a certain negative 'critical' pressure instead of zero pressure as the condition for the free boundary. For systems of horizontal flow, this critical pressure $P_\text{cr}$ can be analytically derived as [Bouwer, 1964 and references therein]

$$P_\text{cr} = \left( \int K \, dP \right) / K. \quad (1)$$

Thus, $P_\text{cr}$ and $K$, are the width and height of a step function with the same area as that under the actual curve of $K$ versus $P$ (Figure 1). The integral should theoretically be between $P = 0$ and $P$ at field surface. However, the reduction in $K$ with decreasing $P$ is usually so great that any $P$-value whereby $K$ is negligibly small compared with $K_\text{cr}$ may serve as the lower limit.
Fig. 1. Schematic relationships between hydraulic conductivity and soil water pressure head for sorption and desorption.

For systems of downward flow, the critical pressure is not so readily defined as for horizontal flow, unless the \( K-P \) curve already approaches a step function. For the case of \( K \) gradually decreasing with decreasing \( P \), however, a digital computer solution with the actual \( K-P \) curve [Reichenbauer, 1963] and an analog solution with the corresponding step function for a system of canals seeping showed excellent agreement [Bouwer, 1964]. Thus, use of \( P_e \) as defined by equation 1 apparently also accounts accurately for negative-pressure flow in systems of mainly downward movement of water.

The parameter \( P_e \) describes the 'equivalent' pressure condition not only where the system is in contact with atmospheric air in the soil at a free boundary, but also where it is in contact at a fixed boundary. The fixed boundary may occur at the bottom of a saturated layer draining into underlying, more permeable, unsaturated material (clogged bottoms in channels or basins, perching layers, etc.). As discussed by Bouwer [1964], \( P_e \) of the unsaturated underlying soil can then be used to approximate the pressure condition at the bottom of the saturated layer.

In view of the apparent usefulness of \( P_e \) and the difficulty of experimentally determining representative \( K-P \) relationships from which \( P_e \) could be calculated for specific soils, direct measurement or estimation of \( P_e \) would be advantageous. Of the various soil parameters that lend themselves to direct measurement, the air entry value \( P_e \), is probably the closest approximation of \( P_e \), for desorption (Figure 1), particularly in soils with sharp reductions in \( K \) at the point of air entry [Reichenbauer, 1963]. The question then is how the air entry value (preferably of soil in place) can be measured and how valid the resulting value is as an estimate of \( P_e \). This question will be discussed in the remainder of the paper.

The field device that was developed for measuring the air entry value also enabled measuring the hydraulic conductivity of the soil. The validity of the hydraulic conductivity thus obtained was also investigated.

**Measurement of Air Entry Value**

**Principles.** The air entry value as used in this paper refers to the pressure head of the soil water when air of zero gage-pressure enters soil with a continuous water phase. This pressure head, indicated as \( P_e \) in Figure 1, is negative and is expressed in cm water.

Techniques whereby \( P_e \) is determined from the pressure at which air enters a prewetted soil surface are unsuitable, because scaling of the surface during prolonged wetting is often difficult to avoid. Thus, the measurement of air entry value should preferably be based upon the entry of air at the bottom of a wetted zone. To accomplish this, water is applied under relatively high head to a covered infiltration cylinder (Figure 2) to create a wetted zone with predominantly positive water pressures and with a sharp front. When the wet front is expected to have reached a depth approximately equal to the cylinder penetration, the water supply valve is closed. This condition creates a continuous body of essentially static water inside the cylinder above the ground and in the wetted zone. Upon closure of the supply valve, the pressure in this water decreases because of a suction exerted by the finer pores in the soil below the wet front. As illustrated in Figure 3, the initial rapid reduction of the pressure head inside the cylinder is followed by a more gradual drop to a minimum, after which a slow and then an abrupt increase takes place. Observations on laboratory columns showed that the minimum pressure head occurs at incipient entry of air at the bottom of the wetted zone. Thus, referring this pressure head to the elevation of
Significant Parameters

Fig. 2. Field device for measuring soil water pressure head at air entry and hydraulic conductivity.

the bottom of the wetted zone yields $P_a$. As air continues to move upward into the wetted zone, the level where air entry occurs increases in elevation, which results in a gradual increase in pressure inside the cylinder. The abrupt increase occurs when air has reached the surface and escapes in the form of bubbles.

In the same manner that $P_a$ for desorption is estimated as the air entry value $P_a$, $P_e$ for sorption will be estimated as the water entry value $P_e$ (Figure 1). The latter parameter has also been called the air exit value [Peck, 1965]. Since $P_e$ is not as easily measured as $P_a$, it would be advantageous if an estimate of $P_e$ could be obtained from $P_a$. Information regarding $P_a$ and $P_e$ for different soils is limited. Available data, such as those of Corey et al. [1965], Topp and Miller [1960], and Watson [1965], seem to indicate, however, that $P_a$ is relatively close to 0.5 $P_e$. Thus, until more information becomes available and refinements in this figure can be made, $P_a$ for sorption will be taken as 0.5 $P_e$.

Field procedure. The field device as sketched in Figure 2 consists of a metal cylinder of approximately 25-cm diameter. A ready-made flange of rolled angle iron is welded to the top of the cylinder and a closed-cell foam-rubber gasket is cemented to the flange. The lid consists of 19-mm-thick (½-inch) plastic sheeting and is clamped to the cylinder with four C-clamps. The supply reservoir consists of a plastic cylinder approximately 8 cm in diameter and 20 cm high. The reservoir is connected to the lid by an 80-cm section of 19-mm (½-inch) galvanized steel pipe with a valve at the bottom. The vacuum gage (30-cm mercury or similar gage) is equipped with a memory pointer. Depending on the depth at which a measurement is desired, the cylinder is installed at soil surface or at the bottom of a hole, trench, or

Fig. 3. Example of pressure head (with respect to soil surface) inside cylinder for medium sand. The depth of the wet front was 10 cm.
other excavation. A driver with sliding weight and cylindrical base resting on the cylinder is used to drive the cylinder approximately 10 cm into the ground. To ensure a good bond between cylinder and soil, the soil is packed down and against the cylinder wall. In case of bare soil, the surface is covered with a protective layer of coarse sand. A disk is placed in the center of the cylinder to dissipate the energy of the water stream from the supply pipe. The lid assembly with the air valve open and the gage and supply valves closed is positioned on the cylinder so that the air-escape valve is at the highest point. The lid is clamped to the cylinder and lead weights are placed on the lid to offset the hydrostatic lift that will be developed by the elevation of the reservoir.

The reservoir is filled and the supply valve is opened while the water supply to the reservoir is maintained. Water now enters the cylinder and the air-escape valve is closed when all the air is driven out. When a sufficient volume of water has entered the soil to create a wetted zone approximately 10 cm deep (as determined by a few trial runs), the supply valve is closed, the gage valve is opened, and the lead weights are removed. As soon as minimum pressure has occurred, which is evidenced by the loss of contact between the gage needle and the memory pointer, the memory pointer is read, the gage valve is closed, and the air valve is opened. The lid assembly is quickly removed and the depth of the wet front is measured by pushing a metal rod into the soil and observing the depth where the penetration resistance increases significantly. Other methods would be to remove the water and the cylinder quickly and to observe directly the depth of the wet front using a spade, or to use dyes or electric conductivity probes. To facilitate accurate assessment of the depth of the wet front, the soil should not be too wet at the time of the test. The air entry value is calculated as

\[ P_a = P_{\text{min}} + G + L \]  

where

- \( P_a \) = air entry value of soil, expressed as pressure head in cm water at point of air entry.
- \( P_{\text{min}} \) = minimum pressure head in cm water as determined by the maximum reading on the vacuum gage.
- \( G \) = height of gage above soil surface in cm.
- \( L \) = depth of wet front in cm.

In equation 2, \( P_a \) and \( P_{\text{min}} \) are relative to atmospheric pressure and are therefore negative. Thus, if the maximum gage reading is 83 cm negative pressure, or \( P_{\text{min}} = -83 \text{ cm water} \), and if \( L + G = 47 \text{ cm} \), the resulting \( P_a \)-value is \( -36 \text{ cm water} \). This value would then give an estimated \( P_{\text{er}} \)-value of \( -36 \text{ cm water} \) for desorption and \( -18 \text{ for sorption} \).

The 8-cm diameter of the reservoir and the 80-cm length of the steel pipe supporting it are suitable for fine and medium textured soils. For coarse textured soils, a reservoir of larger diameter and/or a shorter section of steel pipe may be preferable owing to high infiltration rates.

To reduce the time required for the minimum pressure to be reached, the air inside the cylinder should be completely driven out by the water, and a pressure-measuring device with small displacement should be used. With these precautions, the time for minimum pressure to be reached may range from a few minutes to an hour after closing the supply valve, depending on the pore sizes and the initial moisture content of the soil.

**Measurement of hydraulic conductivity**

The flow conditions in the wetted zone below the device of Figure 2 during infiltration are those pertaining to sorption. Thus, although \( P \) is positive for all but the bottom part of this zone, \( K \) is less than the saturated hydraulic conductivity \( K_s \) (Figure 1), because of entrapped air. Information regarding the relation between \( K \) at \( P = 0 \) for sorption and \( K_s \) for different soils is limited. Available data, such as those of Corey et al. [1965], Topp and Miller [1966], and Watson [1965], indicate that \( K \) at \( P = 0 \) for sorption may range from 0.4 \( K_s \) to 0.6 \( K_s \). Based on these results, \( K \) in the wetted zone during infiltration is assumed to be 0.5 \( K_s \).

The pressure just above the wetting front is the water entry value \( P_{wa} \), which is taken as 0.5 \( P_a \).

From column studies, it appeared that the position of the wetting front was essentially constant from the time that the supply valve was closed to the time that minimum pressure in the water above the soil was observed. Therefore, the depth of the wetted zone just before closing
the supply valve will essentially be equal to \( L \) as measured at the completion of the test. Since the tests are conducted with \( L \) approximately the same as the depth of penetration of the cylinder, the flow in the wetted zone can be considered one-dimensional. Thus, if the infiltration rate immediately before closing the supply valve is known, \( K \), of the soil in the wetted zone can be calculated using Darcy's equation. The resulting expression is

\[
K = \frac{2dH/dt \cdot L \cdot R_c^2}{(H_c + L - \frac{1}{2}P_c)}
\]  

(3)

where

\[
dH/dt = \text{rate of fall of water level in reservoir just before closing supply valve.}
\]
\[
H_c = \text{height above soil surface of water level in reservoir at time supply valve is closed.}
\]
\[
R_c = \text{radius of reservoir.}
\]
\[
R_e = \text{radius of cylinder.}
\]

The rate of fall of the water level prior to closing the supply valve can be measured by taking several time and water level readings, plotting these readings on graph paper, and determining the slope of the resulting curve just before closing the valve. If it is desired to know \( K \) at \( P = 0 \) for sorption, the factor 2 in equation 3 is omitted.

The error in using 0.5 \( P_e \) as estimate of the water pressure at the bottom of the wetted zone has a reduced effect on the error of \( K \) because the numerical value of 0.5 \( P_e \) is added in the equation to \( H_c + L \), which may be approximately 100 cm. Relatively high values of \( H \) are thus desired, not only to obtain positive pressures for most of the wetted zone and a sharp wetting front, but also to minimize the error in \( K \).

The hydraulic conductivity measurement with the device of Figure 2 is similar in principle to that with the cylinder permeameter technique by R. J. Winger as described by Beerman [1965] and with the falling-head permeameter mentioned by Robinson and Rohrer [1959]. The new device, however, eliminates the need for tensiometers used with Winger's equipment, and it requires less time and less water per test. It also removes the uncertainties regarding flow length and total head loss that limited the utility of the falling-head permeameter.

**Validation of Results**

As discussed in the previous sections, the techniques advanced in this paper are based on the following approximations and generalizations:

\[
P_{e,\text{fr}} = \frac{\text{for desorption equals } P_{e,\text{fr}}}{P_{e,\text{fr}} = \text{for sorption equals } P_{e,\text{fr}}}
\]
\[
P_{e,\text{fr}} = \frac{0.5 \cdot P_{e,\text{fr}}}{K \text{ at } P = 0 \text{ for sorption equals } 0.5 \cdot K_{e,\text{fr}}}
\]

The maximum error due to the flat 1:2 ratios in the last two items may range from 10 to 20%. As more data become available, however, refinements in these ratios may be possible.

To obtain experimental information regarding the validity of the results yielded by the device of Figure 2, laboratory and field studies were conducted. In discussing the results, it should be remembered that \( P_{e,\text{fr}} \), \( P_{e,\text{fr}} \), and \( P_{e,\text{fr}} \) are negative. Thus, a value of −40 cm is higher than −60 cm, and a change from −40 to −60 cm is a decrease!

**Air entry value.** The technique of measuring \( P_e \) with the device of Figure 2 should yield results that are independent of \( H \), \( L \), and the initial moisture content of the soil. This expectation was verified with studies in the laboratory, using vertical soil columns, and in the field with the device of Figure 2. The soil columns were formed in 100-cm sections of rigid plastic tubing with a diameter of 7.6 cm (3 inches). Each section was covered by a lid-assembly similar to that of Figure 2. The principle of operation was also similar, except that the clear plastic tubing permitted direct observation of the wet front.

The effect of \( H \) and \( L \) on the measured value of \( P_e \) was studied with air-dry 70/30 glass beads in the columns. The results (Table 1) show a slight increase in \( P_e \) with increasing \( L \) for \( H = 40 \) and 100 cm. This increase may be due to a decrease in sharpness of the wet front, which would cause the effective \( L \) to be less than is indicated by the bottom of the wetted zone. The effect of \( L \) on \( P_e \) was, however, not detectable for \( H = 10 \) cm, where the greatest effect would be expected due to the decreasing sharpness of the wet front with decreasing \( H \). The effect of \( H \) on \( P_e \) differs for the different \( L \)-values and it is, therefore, probably overshadowed by experimental errors. The results show that as long as \( H \) is large enough and \( L \) small enough to create a high degree of saturation and a sharp termination of
TABLE 1. Results of $P_v$-Measurements on Glass-Bead Columns

<table>
<thead>
<tr>
<th>$H_v$</th>
<th>$L_v$</th>
<th>$P_{sv}$</th>
<th>Replications</th>
</tr>
</thead>
<tbody>
<tr>
<td>cm</td>
<td>cm</td>
<td>cm water</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>$-64 \pm 3.4$</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>$-65 \pm 1.2$</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
<td>$-66 \pm 2.7$</td>
<td>3</td>
</tr>
<tr>
<td>40</td>
<td>10</td>
<td>$-64 \pm 2.0$</td>
<td>6</td>
</tr>
<tr>
<td>40</td>
<td>30</td>
<td>$-65 \pm 2.2$</td>
<td>4</td>
</tr>
<tr>
<td>40</td>
<td>50</td>
<td>$-58 \pm 3.4$</td>
<td>5</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>$-60 \pm 5.4$</td>
<td>4</td>
</tr>
<tr>
<td>100</td>
<td>30</td>
<td>$-63 \pm 2.6$</td>
<td>5</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
<td>$-59 \pm 4.8$</td>
<td>5</td>
</tr>
</tbody>
</table>

The validity of $P_v$ and 0.5 $P_v$ as estimates of $P_{sv}$ for desorption and sorption, respectively, was investigated for 50 to 500 $\mu$ sand. The values of $P_{sv}$, calculated from $K$-$P$ relationships obtained with the steady-state method [Childs and Collin-George, 1950], were $-64$ and $-38$ cm, respectively [Bouwer, 1964, Table 1]. These values compared favorably with the estimates yielded by $P_v$, which were $-50$ and $-50$ cm.

Since $P_v$ is determined by the larger pores of the soil, the structural condition of the soil will have a considerable effect. For example, $P_v$ for Adelanto loam was approximately $-175$ cm after drying, crushing, and packing the soil in columns. In the field, $P_v$ was $-33$ cm for bare surface soil that had been subjected to moderate traffic. For the root zone of a Bermuda grass crop in the same soil, $P_v$ ranged from $-10$ to $-5$ cm, which shows the importance of obtaining field data for analyzing the behavior of field systems.

Hydraulic conductivity. The validity of equation 3 was tested in laboratory and field studies. Four vertical columns of fine river sand with a $P_v$-value of $-46$ cm water were wetted from above under a 50 cm head. The application of water was halted to determine $K$ according to equation 3. It was then resumed to wet the rest of the column. A certain head was then maintained, so that $K$ could be calculated from the flow rate and head loss for the entire column. Since the latter $K$ was measured a few minutes after the column was completely wetted, the resulting value pertained to sorption. Therefore, the factor 2 in equation 3 was omitted for this comparison. The result given below show satisfactory agreement.

$$K \text{ from equation 3,} \quad K \text{ from entire column,}$$

<table>
<thead>
<tr>
<th>cm/min</th>
<th>cm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.22 \pm 0.026$</td>
<td>$0.20 \pm 0.010$</td>
</tr>
</tbody>
</table>

The $K$-values for the entire column are somewhat less than those from equation 3, which may be partly owing to a higher degree of compaction and/or more entrapped air in the lower part of the column.

In the field studies, $K$, was measured with the device of Figure 2 for Adelanto loam. The tests were carried out in trenches of increasing depth to obtain a $K_v$-profile. The following results were obtained.

<table>
<thead>
<tr>
<th>Moisture content, $%$</th>
<th>$P_{sv}$</th>
<th>Number of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-14</td>
<td>$-34 \pm 11$</td>
<td>13</td>
</tr>
<tr>
<td>14-20</td>
<td>$-32 \pm 7$</td>
<td>11</td>
</tr>
</tbody>
</table>
Depth below surface, cm/min, $K_r$ Number of tests
0 0.12 ± 0.015 22
18 0.060 ± 0.006 22
30 0.042 ± 0.005 21
50 0.042 ± 0.005 21

The rather constant value at depths greater than 30 cm compared favorably with the value of 0.035 cm/min obtained previously at the same location with a double-tube measurement at approximately 80-cm depth [Douwe, 1952]. The data also agree with prior double-tube measurements approximately 50 m from the trench location, which yielded an average of 0.000 cm/min for 9 tests.

Model studies. Systems of lateral flow through soil were set up that enabled determination of $K_r$ and $P_*$, for sorption and desorption from flow rates and water table positions. These values were then compared with $K_r$ and $P_*$ as determined with the device of Figure 2. An example of one of the flow systems, determined by resistance network analog, is shown in Figure 4.

The models consisted of wooden boxes 150 cm long, 60 cm wide, and 150 cm deep, filled with soil to a depth of 100 cm. The drains on opposite sides of each box were 10 × 20 cm in size and consisted of epoxied sand and gravel. Using constant-level reservoirs, a head difference of 2 cm was maintained between the drains to create a system of mainly horizontal flow. This flow was maintained for a number of days, using a recirculatory system and heating the water entering the models to above ambient temperatures to dissolve entrapped air in the soil. Clogging of the drains was averted by periodic reversal of the flow direction. Biological activity in the models was reduced by dosing the water with liquid chlorine. The soil materials used in this study were medium river sand and Laveen loam of the following analyses:

<table>
<thead>
<tr>
<th>Material</th>
<th>Size (mm)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium river sand</td>
<td>0.1-0.5</td>
<td>35%</td>
</tr>
<tr>
<td></td>
<td>0.5-1.0</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>&lt; 0.1</td>
<td>15%</td>
</tr>
<tr>
<td>Laveen loam</td>
<td>0.01-0.05</td>
<td>40%</td>
</tr>
<tr>
<td></td>
<td>0.05-0.2</td>
<td>35%</td>
</tr>
<tr>
<td></td>
<td>0.2-0.5</td>
<td>20%</td>
</tr>
</tbody>
</table>

The conductance of the flow system, symbol $C_r$, is defined in this case as the flow per unit width of the box and per unit head difference. The relationship between the dimensionless ratio $C/K_r$ and the height $y$ of the flow system that is effectively at saturated hydraulic conductivity was determined by resistance network analog (Figure 5). It was also established by analog that the effect of vertical flow components in the models could be ignored. Thus, the effective height of the capillary fringe was $-P_*$, and $C/K_r$ was the same for a mildly sloping water table as for an essentially horizontal water table of the same average height. The height of the flow system that is effectively at $K_r$ can be expressed as

$$y = h - P_*$$

where $h$ is the average height of the water table above the box bottom (calculated as the average height of the water levels in the constant-level reservoirs).

The test procedure consisted of the following steps:

1. Starting with dry soil, water was slowly admitted to the constant-level reservoirs, which were set with a head difference of 2 cm and $h = 25$ cm. The flow rate through the box was measured until it was constant.

Fig. 4. Streamlines and equipotentials for system of lateral flow in model studies.
2. The reservoirs were slowly raised to about 2 cm below the soil surface in the box. A head difference of 2 cm between the reservoirs was maintained, and the flow rate through the box was measured until it was constant.

3. The reservoirs were slowly lowered to $\bar{h} = 25$ cm and the procedure under A was repeated.

For test 2, the height of the flow system effectively at $K_s$ was equal to the total depth of soil in the box, so that $C/K_s$ could be evaluated from Figure 5. Knowing $C$ from the flow measurements for this test, $K_s$ could be computed. This value was then used to calculate $C/K_s$, from the flow rate for test 1. From Figure 5, the effective height of the flow system could then be determined and, knowing $\bar{h}$, $P_{cr}$ could be calculated with equation 4, yielding $P_{cr}$ for sorption. $P_{cr}$ for desorption was calculated similarly from the results of test 3.

The value of $K_s$ as calculated from test 2 applied mainly to the horizontal direction. Since $K_s$ as evaluated with the device of Figure 2 applies to the vertical direction, an estimate of the vertical hydraulic conductivity in the models was also desired. For this purpose, a test with water standing above the soil surface and flow to each drain was made between tests 2 and 3. A curve for this case similar to Figure 5 was obtained by analog, so that $K_s$ could be calculated for the ponded system.

The model studies were carried out in duplicate for the river sand and in triplicate for the Laveen loam. For the same soil materials, $P_s$ and $K_s$ were determined with the device of Figure 2, using 5 replications per soil. The average results (Table 2) show good agreement between $P_{cr}$ and $K_s$ from the field device and from the model studies. An exception is $K_s$ of the river sand, where the density of the surface layer, to which $K_s$ from the field device applies, was probably lower than the density of the deeper sand in the flow models. The Laveen loam was a more cohesive material, and packing surface layers to high density was accomplished for this soil more easily than for the cohesionless river sand.

**DISCUSSION**

The results of the various studies in the previous section support the validity of the four approximations listed at the beginning of that section. It thus appears that the field device of Figure 2 yields reasonable estimates of $P_{cr}$ and $K_s$ for sorption and desorption, which can be used as input information in the analysis of a variety of flow systems, steady as well as transient. For transient systems, filling or draining of pore space is considered to take place at the $P_{cr}$ isosteric line.

Earlier attempts to include negative-pressure flow by taking a certain negative pressure as the condition at the free boundary consisted of the use of the static height of capillary rise for this...
Table 2. Comparison between $P_e$ and $K_s$ from Flow Models and from the Device of Figure 2

<table>
<thead>
<tr>
<th></th>
<th>$P_e$, sorption, cm water</th>
<th>$P_e$, desorption, cm water</th>
<th>$K_s$, lateral, cm/min</th>
<th>$K_s$, vertical, cm/min</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flow models</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>River sand</td>
<td>-16</td>
<td>-28</td>
<td>0.71</td>
<td>0.55</td>
</tr>
<tr>
<td>Laveen loam</td>
<td>-22</td>
<td>-47</td>
<td>0.016</td>
<td>0.015</td>
</tr>
<tr>
<td><strong>Field device</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>River sand</td>
<td>-16</td>
<td>-31</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>Laveen loam</td>
<td>-25</td>
<td>-51</td>
<td>0.015</td>
<td></td>
</tr>
</tbody>
</table>

pressure [Polubarinova-Kochina, 1962]. This assumption could, however, overestimate the flow at negative pressures. Averjanov [1949] proposed the use of three-tenths of the height of capillary rise. Childs [1957] and others have defined the height of the capillary fringe as the $P_e$-value that must be reached before any substantial amount of soil water is released, as shown by the relationship between the water content of the soil and $P_e$. The principles of air entry into the wetted zone below the device of Figure 2 are similar to those of air entry due to air compression ahead of an advancing wet front. Peek [1965] states that the pore air pressure required to initiate air escape from a vertical bounded column can be expected to be equal to the water pressure at the bottom of the minimum depth of the saturated zone plus the air entry pressure of the material.

The air pressure below the wetted zone of Figure 2, however, is taken as zero (gage), so that in that case the water pressure at the bottom of the wetted zone at incipient entry of air is numerically equal to the air entry value of the wetted zone, as expressed by equation 2.

The reduction in the infiltration rate of water into soil due to compression of air ahead of the wet front has received the attention of various investigators [Dickie and Levan, 1965; Peek, 1965; Wilson and Lathin, 1963]. The $P_e$-value as measured with the device of Figure 2 at the desired depth in the profile gives the maximum pressure difference between the soil air below the wet front and the soil water above the wet front. Knowing this difference will make possible evaluation of the maximum reduction in infiltration due to restricted air movement below the wet front.

The infiltration of water below recharge or disposal basins or similar facilities where water infiltrates under relatively high heads is treated by Dickie and Levan [1965] as a system of an advancing saturated zone. For such systems, the initial permeability in the wetted zone can be taken as 0.5 $K_s$, which may be increasing to $K_s$, if the air content of the infiltrating water is less than the saturated air content. If air movement below the wet front is not restricted, the pressure at the advancing wet front can be taken as 0.5 $P_e$. If air movement is restricted, the analysis may be repeated with $P_e$ as the maximum pressure difference between the soil water at the wet front and the compressed pore air below it. This analysis will again show the maximum effect that air compression ahead of the wet front could have on the recharge rate.

Summary

A field device for measuring air entry value $P_e$ and saturated hydraulic conductivity $K_s$ of initially unsaturated soil is described. The device consists essentially of an infiltration cylinder with lid, standpipe, and vacuum gage. Tests are normally completed in 15 to 60 minutes. The resulting values of $P_e$ and $K_s$ constitute the width and height, respectively, of a step function, which is used as a simplified relationship between hydraulic conductivity and (negative) soil-water pressure for desorption. The corresponding values for the step function for sorption are taken as 0.5 $P_e$ and 0.5 $K_s$. The validity of this generalization, which is based on limited available data, is supported by the results of field and laboratory studies. The step functions permit
inclusion of negative-pressure flow in the solution of steady or certain transient flow problems by analyzing the systems on the basis of uniform hydraulic conductivity (K, for desorption, 0.5 K, for sorption) and a negative pressure (P, for desorption, 0.5 P, for sorption) at free or fixed boundaries where the system is in contact with atmospheric air in the soil. Other applications of P, include determining the maximum effect of air compression ahead of an advancing wet front on the rate of water movement into the soil, for instance in connection with infiltration of water into soil with restricted air movement.

REFERENCES


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