A CASE STUDY ON INFILTRATION INTO DRY CLAY SOIL
II. PHYSICAL MEASUREMENTS*

J. BOUMA, L.W. DEKKER and J.H.M. WÖSTEN

Soil Survey Institute, Wageningen (The Netherlands)

(Received March 17, 1977; accepted November 14, 1977)

ABSTRACT


Small infiltrometers were used to measure infiltration rates into strongly and moderately developed compound prisms, sampled individually from surface layers of two dry clay soils. Initially, both rates were equally high but after three hours a higher rate was measured for the moderately developed compound prisms. These data were used to interpret adsorption and outflow phenomena of water in undisturbed, large and initially dry soil cores (diameter 20 cm) sampled from the upper 20 cm of the two soils, following application rates of about 8 mm/h and 28 mm/h. The two soils adsorbed an average of 6.4 mm water before the start of discharge, independent of the applied intensity. They discharged water at a constant and high rate for several hours, allowing adsorption of about 10% of the applied water. This represents a high degree of "short-circuiting" for all treatments, except one: adsorption was 40% at the 28 mm/h rate for the soil with the moderately developed prisms. The moisture content in the transmission zone was not constant as it would have been in homogeneous soil but increased regularly as a function of time. Slow wetting of both soils through a crust, followed by rain with an intensity of 30 mm/h, resulted in the adsorption of only about 3% of the applied rain in both soils.

In general, more effective wetting of a dry clay surface soil at a given rainfall intensity is initially associated with less "short-circuiting" to deeper horizons. However, the resulting higher moisture content allows less adsorption in the surface layer and is therefore associated with increased "short-circuiting" thereafter, as long as large vertical pores have not been closed by swelling.

INTRODUCTION

Infiltration of dyed water followed by field observations of the resulting stains in soil was used to develop empirical relationships between deep infiltration patterns and the flow regime in four dry clay soils (Bouma and Dekker, 1977). The experiments, reported in this paper, were designed to test these results and, if feasible, express them in quantitative terms. These experiments will be discussed in three groups, as follows.

* Contribution from the Soil Survey Institute, Post Box 98, Wageningen, The Netherlands.
(i) *Determination of the vertical infiltration rate into initially dry prismatic peds.* Dry clay soil is characterized by vertical shrinkage cracks, which can conduct large volumes of water. For example, measured percolation rates of *ponded water*, ranged between 11 and 75 m/day in our dry soils (46 cm/h and 313 cm/h, respectively). Of more relevance is the infiltration of rain because ponded conditions do not occur. But even then, deep penetration may occur at relatively low application rates and applied quantities, as evidenced by dye studies (Bouma and Dekker, 1978). Water will only flow into large pores, which generally occur between peds in these soils, if the finer pores inside the peds cannot conduct liquid applied at a given intensity. This can be the case instantly, or after a certain period when the infiltration rate into the peds has decreased to a level below that of the applied intensity. The overall capacity of these soils to accept liquid is thus determined by flow processes at two levels: first, by the system of large interpedal pores, and, second, by the porous system inside the peds (see also Klute, 1973). Physical measurements on clay soils should reflect this difference. Very large samples must be used to adequately represent effects of the interpedal pores. Smaller samples, to be obtained on the basis of a morphological analysis, should be used to characterize flow into the peds. The latter was investigated in this study in two dry clay soils.

(ii) *Determination of the water distribution in dry clay soils after different flow regimes.* Observation of stains in soil provides information as to the maximum depth of infiltration through large pores, but the distribution of water in the soil above that depth remains unknown (Bouma and Dekker, 1978). Knowledge of this distribution of water in the soil as a function of the applied flow regime is important to determine, for example, the efficiency of spray irrigation or the effects of different rain intensities on availability of water for plant growth. Traditional soil physical tests, with the possible exception of gravimetric moisture content, cannot be applied due to the heterogeneity of the infiltration pattern, which results in large differences among moisture contents of soil at short distances. Bulk moisture content measurements with neutron-probe or gamma-ray equipment are therefore meaningless, as are random tensiometric measurements of pressure potentials. Even the determination of gravimetric moisture contents, following in situ sampling on the basis of visual observations, is difficult to express in representative terms for an entire horizon. Laboratory experiments, using large undisturbed samples (20 cm high, 20 cm diameter) of two dry clay surface soils, were therefore made in this study to obtain a measure for the water retained in a particular bulk volume of soil following different flow regimes.

(iii) *Determination of the effect of wetting of surface soils on infiltration.* Infiltration into dry clay soil involves some degree of wetting of the surface layer as soon as water is applied. This results in a gradual decrease of the infiltration rate into the peds, as they become wetter and swell. Linear extensibility values at saturation, determined with the saran method (Grossmann et al., 1968) were 0.13, which is high. Swelling may ultimately result in the closing of some of the larger pores, forcing the water to flow through rather
than around the prisms. Then, infiltration rates and possible "short-circuiting" of water from the soil surface to deeper soil horizons are greatly reduced. However, before that time the effect of the decreasing infiltration rate into the ped could result in increased "short-circuiting" along large continuous pores, but only, of course, when those are not yet closed by swelling. Some exploratory laboratory experiments were made to illustrate the effects of continued wetting in two of our soils.

SOILS AND METHODS

Samples were taken from two Typic Fluvaquents (very fine clayey, mixed, mesic) with contrasting macrostructure, described as Soils I and II in a companion paper (Bouma and Dekker, 1978). Moisture contents in the field at the moment of sampling corresponded with pressure potentials of approximately --15 bar as estimated from moisture retention data. The soil was therefore considered to be "dry" (Soil Survey Staff, 1975).

Infiltration rates into individual dry prisms were measured with small 7.5-cm diameter infiltrometers described by Falayi and Bouma (1975). The upper 8 cm of a prism was carefully carved out to fit the (grease-coated) interior of the infiltrometer, which was then gently pushed down around it.

The prism with the infiltrometer on top was then put into a plastic cylinder into which gypsum was poured to form a rigid encasing half-way up the infiltrometer (Fig. 1). Infiltration rates into the single prisms were measured using a burette with a Mariotte device (Fig. 1), which maintained a shallow hydraulic head on top of the prism. The prisms were generally about 25 cm high and had a diameter of about 10 cm. Outflow at the bottom could occur freely. Compound prisms were sampled at around 20 cm depths in Soils I and II and some single prisms were obtained at around 40 cm depths in both soils. In addition, duplicate undisturbed cylindrical soil cores with a diameter and height of 20 cm were sampled in a plastic cylinder, with grease-coated interior to avoid boundary flow. The cylinder was gently pushed around a cylindrical column of soil, previously carved out in situ from the soil surface downwards. This column contained several prisms in their natural arrangement including interpedal pores. The grass on the core was cut to a height of only a few centimetres, as in the corresponding field experiments. A plastic covered wooden frame on four legs was built with a rectangular shape and horizontal dimensions of 0.5 X 1 m, corresponding with the size of the field plots (Fig. 2). A cylindrical hole was made in the centre of the frame with a slightly larger diameter than that of the soil core to allow unimpeded, vertical movement of the core for weighing purposes. A fragment of plastic was used to avoid water movement between the wall of the core and the surrounding frame (Fig. 2). The core was placed on a heavy-duty balance by means of a stand which allowed sampling of percolating liquid in a beaker.

First, the infiltration rate for "ponded" conditions was determined by ponding water on the core for a very short period, not exceeding a few minutes.
(to avoid too much wetting) and by measuring the percolation rate. This flux cannot be used to calculate $K_{sat}$ because the entire soil is not saturated, but it is a relative measure for movement in continuous large, vertical pores.

After drying of the core, water was sprayed on the entire wooden frame at intensities of 8 mm/h and 32 mm/h, exactly simulating experimental procedures used in the field (Bouma and Dekker, 1978). The same cores were used for both intensities with one exception (Table I). The initial, low moisture content was re-established after the measurement of one flow intensity by air-drying the wetted core. This procedure would not be acceptable for many other soils due to lack of reversibility in wetting and drying. However, small quantities of water were adsorbed by these soils as will be shown later (Table I). This water infiltrated superficially at the top of the core and along prism faces, where removal by evaporation is quite feasible. The procedure allows comparisons between different application rates in the same porous medium. Use of replicate samples would have complicated comparisons due to natural variability.
Fig. 2. Schematic cross-section of the experimental set-up for measuring the adsorption and outflow of water in large undisturbed soil cores at application rates of around 8 and 28 mm/h.

TABLE I

Physical data, calculated to document the effects of different flow regimes through large undisturbed cores from the upper 20 cm of two dry clay soils with contrasting macrostructure

<table>
<thead>
<tr>
<th>Soil core</th>
<th>Initial moisture condition (vol.%)</th>
<th>Inflow rate (mm/h)</th>
<th>Period to first outflow</th>
<th>Steady adsorption rate during outflow</th>
<th>Steady outflow rate (mm/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ia</td>
<td>41</td>
<td>8</td>
<td>45</td>
<td>6.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Ib</td>
<td>41</td>
<td>8.6</td>
<td>70</td>
<td>10</td>
<td>1.1</td>
</tr>
<tr>
<td>IIa</td>
<td>36</td>
<td>9.7</td>
<td>45</td>
<td>7.5</td>
<td>1.1</td>
</tr>
<tr>
<td>IIb</td>
<td>38</td>
<td>8</td>
<td>28</td>
<td>3.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Dry soil, low application rate</td>
<td>Ia 41</td>
<td>8</td>
<td>45</td>
<td>6.2</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Ib 41</td>
<td>8.6</td>
<td>70</td>
<td>10</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>IIa 36</td>
<td>9.7</td>
<td>45</td>
<td>7.5</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>IIb 38</td>
<td>8</td>
<td>28</td>
<td>3.7</td>
<td>1.1</td>
</tr>
<tr>
<td>Dry soil, high application rate</td>
<td>Ic 38</td>
<td>26</td>
<td>14</td>
<td>6.2</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td>Ib 38</td>
<td>26</td>
<td>14</td>
<td>6.2</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td>IIa 36</td>
<td>28.5</td>
<td>18</td>
<td>7.5</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>IIb 39</td>
<td>29.5</td>
<td>10</td>
<td>3.7</td>
<td>2.4</td>
</tr>
<tr>
<td>Moist soil, high application rate*</td>
<td>Ic 52</td>
<td>27.5</td>
<td>5</td>
<td>2.5</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>IIa 46</td>
<td>34</td>
<td>15</td>
<td>7.5</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>IIb 48</td>
<td>32</td>
<td>5</td>
<td>3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

* To obtain moist soil, cores Ic and IIa were wetted through a gypsum-sand crust for 5 days and core IIb for nine days.
Water not sprayed on the upper surface of the core in the centre of the frame flowed away over the slightly sloping surface of the frame and was collected in a bucket.

The weight increase of the core and the volume of outflow, both measured as a function of time, could be used to calculate the rate at which water was adsorbed by the soil and the average application rate of water on the core. The latter value deviated somewhat from the average rates of 8 mm/h and 32 mm/h applied to the entire frame (Table I). During the steady outflow phase of these experiments, the weight of the core included a very shallow layer of ponded water on the upper surface. But this layer was of constant thickness as observed during the measurements and did not therefore affect the reported adsorption rates in Table I, because these are based on differences among weights and not on absolute values.

Duplicate columns used for this part of the study were next slowly wetted through a 50% gypsum—sand crust, which was used to avoid short-circuiting of liquid through large vertically continuous pores and to simulate natural slow wetting of a surface layer as observed in the field.

After five days, moisture contents as estimated by weighing had significantly increased. Crusts were then removed, except for column IIb which was wetted for an additional four days (see Results-section). The infiltration rate for ponded conditions was measured rapidly, as described earlier for dry cylinders; then water was sprayed on the cores at an intensity of about 32 mm/h and monitoring occurred as before. Finally, the cores were dried at 105°C. The dry weight and the known volume allowed the calculation of average moisture contents from weights determined during the experiments.

RESULTS AND DISCUSSION

Infiltrations into prisms

Infiltration rates into individual prisms of Soils I and II (sampled around 20 cm and 40 cm depth) were initially high but decreased rapidly within a few hours (Fig. 3). This decrease is in agreement with existing infiltration theory and can be used to interpret the proposed mechanism of infiltration into our dry clay soils which have large vertical pores adjacent to the peds (interpedal pores) (Bouma and Dekker, 1978). The proposed mechanism assumes initial adsorption by the prisms (no deep stains) followed by deep penetration along large vertical interpedal pores (deep stains) as soon as the (constant) application rate started to exceed the decreasing capacity of the prisms to adsorb liquid. The latter is estimated by measuring the infiltration rate into the prisms. The effect on infiltration of the presence of ponded water (as in our measurements of infiltration rates into prisms only) cannot in general be compared with the effects following the application of artificial rainfall on the entire soil if the latter is applied at a lower rate than $K_{sat}$ of the entire soil. However, a shallow layer of free water was also present on the
large cores in the rain experiments, due to the relatively low infiltration rate into the prisms and, particularly, to the low number of vertical flow channels in these particular soils (Bouma and Dekker, 1978). This observation is believed to justify the comparison.

Prisms in Soil I were weakly developed and parted to strongly developed medium angular blocky peds. Those of Soil II were strongly developed parting to moderately developed, medium angular blocky peds (Bouma and Dekker, 1978, fig. 1). Differences among initial infiltration rates into dry prisms of both soils were not significant. However, after three hours, infiltration rates into prisms of Soil II were significantly lower (90% probability) than corresponding values for Soil I. This difference, which appears to be related to the less well developed primary peds in Soil II, may explain the deeper penetration along large pores in Soil II, even more so with the vertical pores between prisms better developed in this soil according to the morphological description (Bouma and Dekker, 1978, fig. 1). Occurrence of better developed vertical pores in Soil II can be specifically illustrated by comparing measured percolation rates under short-duration ponded conditions in large undisturbed cores with dry soil, as described in the methods section. These were 75 m/day and 34 m/day for Soil II and a lower 11 m/day and 18 m/day for Soil I.
Infiltration into large, dry soil cores, including interpedal pores

The monitoring data from applications of two rain intensities to duplicate, large dry soil cores are summarized in Table I. The infiltration process consists of two distinct parts, which will be discussed separately: (1) adsorption of the applied water by the soil before discharge; and (2) discharge of water by the core thereafter at a constant rate for several hours.

Ad (1): In both soils water was adsorbed for a longer time, before discharge, at an intensity of 8 mm/h (average 47 min) than at an intensity of about 28 mm/h (average 14 min). Differences between the two soils, comparing similar intensities, appear to be insignificant, particularly at the high application rate where the average time of 14 min was identical for both soils. The volume of water that was adsorbed in the period before discharge was essentially similar for both intensities in both soils. This conclusion follows from comparing data in Table I for high and low intensity rainfall applied to the same core. For example, in Soil I (core Ib) 10 mm of water were adsorbed for 70 min at an intensity of 8.6 mm/h before water left the core. A quantity of 6.2 mm was adsorbed in the same core during 14 min at an intensity of 26 mm/h. Identical examples can be given for Soil II. In addition, differences among all adsorbed volumes of water before outflow, for all cores, do not appear to be significantly different. This may be due to the initially identical infiltration rates of the dry prisms in both soils (Fig. 3).

We concluded that both surface soils had a rather specific and limited capacity to adsorb liquid before discharge occurred. This capacity was independent of the intensity (when ranging from 8 mm/h to 29.5 mm/h) and of the difference in macrostructure.

Ad (2): The rate of discharge was constant for all soil cores at both rain intensities for several hours and is therefore presented as one rate in Table I. Steady adsorption rates and the steady increase of the average vol.% of moisture in the cores can be calculated from inflow and outflow data (Table I). These are relatively low and not significantly different for both soils, even at different application rates, but there is one exception. A significantly higher volume of water is adsorbed by Soil I at an application rate of 26 mm/h. But even then, only an average 40% of the applied water is adsorbed in the column.

Adsorption of water by the soil cores has to proceed either by infiltration into prisms in the exposed upper surface of the core or laterally from a few vertical bands which conduct water through the core (as shown by stains observed in the field study). Infiltration rates into prisms of Soil I were higher, after a few hours, than those for Soil II (Fig. 3). This difference may explain why more water is adsorbed at the 28 mm/h application rate by prisms in Soil I. More adsorption in the surface layer results in less flow along interpedal pores at a given application rate. Indeed, fewer bands were observed in Soil I as compared with Soil II in the companion field study (Bouma and Dekker, 1978, figs. 2 and 3). Lateral adsorption of water from the vertical bands is bound to be low, due to the small contact area. Moreover, measure-
ments showed that moisture contents in soil underlying stained vertical bands were not significantly higher than those of soil at the same level in the same position, but without bands. We concluded that these surface soils have a constant capacity to adsorb water for several hours (at rain intensities of about 8 and 28 mm/h) as outflow occurs. This capacity, however, is low, which results in outflow of 59–96% of the applied water in these 20 cm high cores (derived from data in Table I). The steady rate of outflow was a function of macrostructure at 28 mm/h but not significantly so at 8 mm/h.

These results deviate, of course, from the behaviour expected using a Darcy-type flow theory for homogeneous soils. Obviously, boundary conditions for the conventional flow theory do not apply to infiltration into dry clay soil (see also Klute, 1973). A basic difference between the observed infiltration patterns and those predicted for homogeneous soil, using a Darcy-type flow theory, is the steadily increasing moisture content of the transmission zone in our experiments (Table I), whereas the theory predicts a transmission zone with a constant moisture content (e.g., Baver et al., 1972).

**Infiltration into wetted surface soil**

Slow infiltration of water through a 50% gypsum–sand crust resulted in a significant increase of the moisture content of the cores after five days (cores Ic and IIa) and nine days (core IIb, Table I). Due to the crust, infiltration must occur in the prisms, because large pores between the prisms remain filled with air. The observed more rapid increase of the water content by Soil I can be explained by higher infiltration rates into prisms of that soil (Fig. 3). Water was applied at intensities ranging from 27.5 to 34 mm/h (Table I). Outflow was again steady at least during the first two hours of observation. Relevant derived data are summarized in Table I. The time to first outflow and the volume of water adsorbed was less in moist soil, particularly in Soil I, as compared with dry soil. The difference must be due to the higher moisture content of the core which allowed less adsorption at the surface and less lateral adsorption from vertical bands. These differences are also clearly indicated by lower steady adsorption rates after the start of outflow (Table I). This effect is very pronounced in Soil I where now only 2% of the applied water is adsorbed, rather than 38% when applied to dry soil. Differences are parallel but smaller for Soil II. Apparently, at this stage of wetting, the effect of the decreasing infiltration rate into the prisms dominates the overall infiltration pattern. Swelling has not yet resulted in closure of the large vertical pores to strongly reduce the possibility of "short-circuiting".

Some continuous large pores are still present after wetting through the crust, as is indicated by the percolation rate under ponded conditions, measured after removal of the crust.

These rates were 4 m/day (Soil I) and 8 m/day (Soil II). These values are much lower than those measured in dry soil (average of 15 m/day and 55 m/day, respectively) but still so high that they suggest presence of some large
continuous voids. Continued swelling will ultimately result in closure of the large pores and in low infiltration rates and possible ponding. Wetting was not continued to this point, but in a related study a large undisturbed core with a height of 30 cm, sampled in Soil I at a depth of 20–50 cm was saturated for 4 months in the laboratory.

The percolation rate (which was 15 m/day when dry) reduced to a steady 5 mm/day after three months, following apparent closure of the large vertical pores by swelling.

Differences between Soils I and II in terms of their “short-circuiting” potential can now be summarized as follows. Soil I has a lower potential when dry, as shown by relatively less dye penetration in the field experiments and higher adsorption rates in the laboratory experiments. Upon wetting of the surface layer which occurred more easily in Soil I, the adsorption of water decreased to the same low level in both soils as outflow occurred, and “short-circuiting” was very high. Better wetting of the surface layer (which in itself limits “short-circuiting” initially in the dry soil) has, therefore, in turn the effect of increasing “short-circuiting”. This can only occur, of course, as long as the larger vertical pores are not closed by swelling.

INTERPRETATION

Practical implications of the “short-circuiting” phenomenon in clay soil depend on the type of land use and may be unfavourable when, for example, soil is used for waste disposal or when plants with shallow root systems are irrigated. On the other hand, the phenomenon may be favourable for plants with deep root systems, because the water will be concentrated in deep cracks where the roots are, whereas the soil surface remains relatively dry and has therefore a relatively high mechanical stability. The stability factor becomes increasingly important in some areas because of farm mechanization and high-intensity dairy operations.

The height of 20 cm of our columns was arbitrary and partly dictated by experimental limitations. But similar experiments can, of course, be made with bigger cores, which, for example, could extend to the depth of rooting.

Most roots in the grassland soils, studied here, were concentrated in the upper 20 cm and our experiments can be used to define optimal spray irrigation procedures to be used in summertime when there is a moisture deficit in The Netherlands. Optimal procedures should use relatively high-intensity rainfall during a short period, allowing efficient use of the expensive equipment over a relatively large area. The exact intensity and duration of application should be such that no appreciable “short-circuiting” occurs beyond 20 cm depth.

Correlations between degree of “short-circuiting” and morphological descriptions of soil structure, as broadly demonstrated in this study, may be potentially valuable tools for field soil scientists to be used for predicting certain aspects of soil physical behaviour of clay soils.
REFERENCES