Characterization of soil macropores by infiltration measurements

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Characterization of soil macropores by infiltration measurements

Ankeny, Mark Dwight, Ph.D.
Iowa State University, 1988
Characterization of soil macropores
by infiltration measurements

by

Mark Dwight Ankeny

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of the
Requirements for the Degree of
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Department: Agronomy
Major: Crop Production and Physiology

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Iowa State University
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1988
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DEDICATION

To Catharine
GENERAL INTRODUCTION

The long term objective of my research is to understand how root growth is affected by tillage systems. In this introduction, root growth and the soil structural properties commonly measured to correlate with root growth are briefly reviewed and the premise that present methods of measuring soil structure often correlate poorly with root growth is developed. From this premise, the conclusion can be drawn that better methods are needed to measure soil structure. A method for measuring unsaturated infiltration as a tool for evaluating soil structure is developed in this dissertation.

Root growth can be limited by various factors. These include temperature, nutrition, pH, and disease as well as limitations imposed by soil structural properties. Soil structural properties alter root growth and root growth alters soil structural properties.

Root elongation occurs when meristem cells behind the root tip elongate and push the root tip forward. As resistance is met, growth of root hairs on epidermal cells behind the meristem occurs. These root hairs anchor the root tip which allows most of the pressure of meristem cell elongation to be transmitted to the root tip (Russell, 1973).

The pressure a root can exert and its resistance to buckling are dependent
upon several factors. These include genetics (which affect root diameter) and the soil water potential. The growth rate of corn roots is halved as water potential decreases to -800 kPa (Peters, 1957). However, as Russell (1973) points out, the direct effect of water potential is usually confounded with increasing soil shear strength as tension increases. In the laboratory, effects of water on root growth and on soil structure can be separated. Russell and Goss (1974) placed barley root systems in a glass bead matrix and applied pressures to the beads ranging from 0 to 100 kPa. They calculated that root elongation dropped steadily to 50% of the control at 20 kPa and to 15% at 100 kPa. The roots became shorter and larger in diameter. The 0 to 100 kPa pressures that Russell and Goss applied to the roots are only a small fraction of the pressure a root is capable of applying to the soil. Taylor and Ratliff (1969) showed that the maximum force a root can exert is usually in the 900 to 1300 kPa range. Therefore, soil resistances approximately one tenth the maximum pressure a root can exert can greatly reduce root growth.

The preceding conclusions suggests that soil strength might limit root growth in pores smaller than the root follows. Goss (1977) grew barley on a bed of rigidly packed glass beads with adequate nutrition and aeration. Pore diameter between glass beads was intermediate between that of root axes and root laterals. The results were barley plants with extensive lateral development and reduced growth of root axes showing that pore size can influence root morphology as well as limit root growth. Russell (1977) declared that if root extension is not to be limited by mechanical forces, the solid soil matrix must either contain continuous pores between structural units, which are large enough for roots to penetrate freely, or
pores that can be expanded, by the root, against only small external resistances from the soil.

From this morphological evidence, minimum pore size for unimpeded growth of a root in soil can be estimated. Assuming roots do not enter rigid pores smaller than their own diameter (Weirsum, 1957) and that soil pore walls provide increasing resistances upon drying, we know the pore size limit to unrestricted root growth in soil with appreciable shear strength is about the same as the root tip diameter. For secondary lateral roots of small grains, this is about 0.1 to 0.3 mm (Hackett, 1969). Macropores have been defined in a number of ways (Luxmoore, 1981), but as a functional definition, a pore larger than a root tip diameter (approximately 0.2 mm) is appropriate. From the capillary rise equation, this means that pores that empty at 15 cm tension (pores of 0.2 mm nominal diameter or larger) will be considered macropores. If the root tip grows in a smaller pore, it will undergo mechanical stress, which will impede its growth. Therefore, in a fine textured soil with high strength, an estimate of pores having a diameter of about 0.2 mm or larger should be correlated with the ability of the plant root system to explore and exploit the soil matrix.

The relationship between root growth and soil structure has been evaluated in several ways. The two soil properties most often correlated with root growth are bulk density and soil strength. Pore size distribution and saturated hydraulic conductivity are often measured to determine tillage effects on soil properties. Each of these techniques is discussed briefly below.

Bulk density and penetrometer resistance describe properties of the soil matrix
rather than properties of the soil pores themselves. Both of these parameters tend to correlate best to root growth under conditions of fairly uniform soil structure. Uniform structure is often the result of tillage operations. Therefore, these measurements are usually most valuable on tilled soils. Bulk density and penetrometer measurements generally have been of less value on untilled soils or in comparisons among tillage treatments. For example, Ehlers et al. (1983) found better oat root growth in untilled soil with both higher bulk density and higher penetrometer resistance than the less dense tilled soil. They postulated that biopores (wormholes, root holes, etc.) more than compensated for increased resistance of the soil matrix as measured by both bulk density and penetrometer resistance.

Another property of soil often measured is pore size distribution. This information is obtained by taking a soil core from the field, saturating it, subjecting it to stepped increases in tension, and determining the volume of pores of a given size by measuring how much water drains from the core as tension is increased. This technique is useful, but has several practical limitations. First, collecting a soil core in the field may destroy some of the large pores of most interest in root growth and water movement. Second, while the fractional volume of given sized pores is most important for water storage, the technique reveals little about pore continuity, which is more important for both water flow and root growth. Third, there is a water potential difference in the core on the tension table that is equal to the height of the core. For example, an 8 cm high soil core at an average potential of 4 cm water tension would have a tension of 8 cm at the top and a tension of 0 cm at the bottom. These tension differences are only a small fraction of the total potential at
higher tensions, but at lower tensions, these differences result in great disparities in water-filled pore sizes from the top to the bottom of the core. Lastly, it takes a lot of labor and several weeks to get the information which limits the use of this technique in research.

Saturated hydraulic conductivity is commonly measured in tillage studies. While it is seldom correlated directly with root growth, it can be used to infer the suitability of the soil as a growth medium (Klute, 1982). A high correlation between saturated hydraulic conductivity and root growth is not expected because the largest pores will conduct nearly all of the water. Flow in the largest pores or cracks will mask flow in intermediate sized pores that also are important for root growth. In addition, the largest pores and cracks are often the most variable, which leads to poor correlations between saturated infiltration rates and root growth.

Another experimental approach for evaluating soil pore structure is to measure unsaturated flow of water into the soil surface. Supplying water under a tension during unsaturated infiltration results in water flow through small pores while large pores are kept empty. By varying tension, different sized pores can be emptied or filled. The smaller the pore, the more tension it takes to empty the pore of water. Rate of water flow through given pore sizes depends on both pore volume and pore continuity. Therefore, a correlation between unsaturated infiltration and root growth is expected. This correlation has not been previously attempted because many factors affect water flow in soil and determination of soil structure from infiltration measurement is not straightforward.

Unsaturated flow of water in soil is affected by initial soil water content, tem-
perature of the water and soil, viscosity of the soil solution, and wettability of pore walls formed in various ways. In addition, unsaturated infiltration rates will be dependent upon the number, continuity, and size of pores. If infiltration is primarily one-dimensional, then flow rate at longer times is relatively independent of soil matric forces. To obtain unsaturated one-dimensional flow in the field, it is necessary to drive a ring into the soil to eliminate lateral flow. However, this ring destroys lateral connections of the pores. The act of pushing a ring into the soil may also disrupt pores within the ring. The measurement choice may come down to a more easily interpreted one-dimensional flow or to a harder to interpret, three-dimensional flow, that is more relevant to three-dimensional soil structure.

Work using devices to control tension on the soil surface has recently become more popular. Names given similar devices reveal some of the different backgrounds leading to unsaturated infiltration measurements: unsaturated sorptivity tube (Clothier and White, 1981); unsaturated sorptivity device (Chong and Green, 1983); closed adjustable head infiltrometer (Topp and Zebchuk, 1985), Guelf permeameter (Elrick et al., 1987); tension infiltrometer (Ankeny et al., 1988); and disk permeameter (Perroux and White, 1988).

The dissertation is divided into three sections. The first two sections contain manuscripts prepared for publication in the Soil Science Society of America Journal. The first, entitled “Design for an automated tension infiltrometer” contains: Introduction, Materials and Methods, Results and Discussion, and References subsections. The second and third sections include the subsections listed above plus a Conclusions subsection. All sections have figures and tables included within the
These sections are followed by an overall Summary and Conclusions of the work undertaken. Additional literature used in the General Introduction and the Summary and Conclusions is cited in the Literature Cited section.
SECTION I. DESIGN FOR AN AUTOMATED TENSION INFILTROMETER
INTRODUCTION

Infiltration under tension has been used to estimate sorptivity (Chong and Green, 1983), unsaturated hydraulic conductivity (Moore et al., 1986), and macro-porosity (Watson and Luxmoore, 1986). The devices used by these researchers are modifications of an infiltrometer originally developed by Clothier and White (1981). Clothier's and White's device consists of an 8.6 cm sintered glass plate for soil contact attached to a Mariotte column. Tension is controlled by a hypodermic needle. Our long-term objective is to use a similar device in the field to characterize macropore structure of agricultural soils. Because a large number of measurements and a range of tensions are required for such a field study, modifications of the design of Clothier and White (1981) were required to provide: (i) quick and accurate tension control at low tensions, (ii) improved measurement precision at low water flow rates, and (iii) automatic measurement and data collection for increased measurement speed and elimination of bubbling-induced variability. This section describes the design and demonstrates the improved performance of a modified tension infiltrometer.
MATERIALS AND METHODS

A schematic diagram of the device used is shown in Fig. 1.1. The major components are a bubble tower, a Mariotte column (water reservoir), a base for soil contact, and a transducer-equipped data logger for data collection and storage. The bubble tower has four air-entry ports that control tension by allowing air entry at different distances below the water level. The ports can be preset to tensions from 0.02 to 0.50 m, and valves are used to switch from one port to another. Watson and Luxmoore (1986) also used a similar valve arrangement to change tension. The bubble tower is connected to the Mariotte column with 1.6 mm i.d. polypropylene tubing (bubbling tube). Electronic monitoring of tension at rapid infiltration rates (> $5 \times 10^{-4}\text{ m s}^{-1}$) has shown that airflow through the bubbling tube is sufficient to limit the flow-induced tension increase at the soil surface to < 5 mm of water above that imposed by the bubble tower.

Interchangeable Mariotte columns of different diameter are employed because the volume of water infiltrating into the soil is calculated from the height change of water in the column. Constantz and Murphy (1987) pointed out that measurement precision is dependent upon the diameter of the Mariotte column. At low rates, use of a small column rather than a large diameter column results in a greater change in height per unit inflow and in improved measurement precision. The use of 6.4-, 12.7-, and 19.0-mm i.d. Mariotte columns gives a ninefold range in volume change per unit change in height and allows measurement of infiltration rates of $1 \times 10^{-8}$ to $5 \times 10^{-4}\text{ m s}^{-1}$. When columns of < 6.4 mm i.d. were used, trapped-air pockets formed below the water surface during bubbling. Smaller columns could be
Figure 1.1: Schematic diagram of tension infiltrometer
used if bubble size is reduced by using a smaller-diameter bubbling tube at the air entry point in the column. Sigmacote (Sigma Chemical Co., St. Louis, MO) was used on the inner wall of the column to reduce water beading, which would decrease measurement precision.

A broadcloth-covered Spex (Spex Industries, Edison, NJ) 400-mesh nylon filter (air entry value of about 250 mm of water tension) is used for soil contact. A finer filter must be used for greater tensions. The filter is backed by a circular 8.9 cm diameter acrylic faceplate. This faceplate has been grooved on a lathe and has approximately one 2-mm hole per 10 mm² to allow relatively unimpeded water flow. This faceplate is glued to a 8.25 cm i.d. acrylic ring that seats in a gasket at the base of the instrument. The resulting infiltration surface has a diameter of 8.25 cm.

Measurement of infiltration has been automated by the use of a Campbell 21X data logger (Campbell Scientific, Inc., Logan, UT) and two Series PX-136 4-wire full-bridge (0-5 PSI gauge type) pressure transducers (Omega Engineering, Stanford, CT). This design is a modification of the single-transducer technique of Constantz and Murphy (1987). When calibrated with a water manometer, these transducers give a linear voltage output as a function of tension ($r^2 > 0.999$). Head-space tension in the Mariotte column is linearly related to the height of water in the column. A unit change in height causes a unit change in tension. Thus, infiltration can be calculated from the change in head-space tension measured by the transducer. One pressure transducer is mounted in the head space at the top of the Mariotte column and the second transducer is mounted near the base of the column, 60 mm above the soil surface. The data logger is programmed to record paired reading of
top and bottom transducers at regular intervals. Additional relevant information, such as Mariotte column diameter and run identification, can also be recorded.

The soil used in this study was collected from the A horizon of a Fruitfield coarse sand (sandy, mixed, mesic Entic Hapludoll) and hand-packed to a bulk density of $1.60 \pm 0.02$ Mg m$^3$ and initial volumetric water content of $0.10$ m$^3$/m$^3$. 
RESULTS AND DISCUSSION

In the first experiment, no water flow into or out of the infiltrometer occurred. A vacuum line was attached to the top of the Mariotte column to cause air bubbling in the column without water flow. Paired readings of the top and bottom transducers were made at the rate of 5 s⁻¹, with the bottom reading occurring about 100 ms after the top reading of the pair. In an ideal system, measured height of the water column would not vary over time if no water flow occurred. In a Mariotte system with electronic data collection, however, estimated water column height is determined from tension measurements, and tension varies as bubbles expand and detach from the bubbling tube. Tension data from the top transducer in Fig. 1.2 show the tension fluctuations in the Mariotte column caused by bubbling. As air was evacuated from the top of the Mariotte column, tension gradually increased and a bubble formed and expanded at the end of the bubbling tube. When detachment of the bubble occurred, tension decreased rapidly. The cyclic rise and fall of tension as bubbles are formed and released results in the characteristic pattern shown in Fig. 1.2. The bottom transducer also measures the same tension fluctuations and would produce a similar pattern. Tension fluctuation in the Mariotte column is proportional to the surface tension of the water-air interface in the bubbling tube and to the change in bubble radius as it expands and breaks free of the bubbling tube. Larger bubbles would result in increased tension variation.

Figure 1.2 also shows that data based on the difference in tension between the top and bottom transducers are less variable than data from the top transducer alone. Standard deviation is reduced from 6.2 to 2.2 mm. Thus, bubble-induced
Figure 1.2: Tension variation over time in a Mariotte water column caused by bubbling without water outflow and measured by using one transducer (T) or using the difference between two transducers (D)

\[ T: SD = 6.2\text{mm} \quad D: SD = 2.2\text{mm} \]
tension fluctuations registered by both top and bottom transducers canceled out when the two values were subtracted. Consequently, the difference in tension between two transducers is dependent only upon height of the water column and not upon bubble size or tension at a given instant. If bubble detachment occurs in the 100 ms after the top transducer reading, however, and before the bottom transducer reading, then the bottom reading will be near its minimum value while the top reading is near its maximum value. This 100-ms delay between the readings, inherent in the data logger, is manifested as the outliers in Fig. 1.2. In this example, there are about 20 paired readings per bubbling interval (5 pairs s$^{-1}$). In a typical infiltration run, however, paired data readings would be collected less frequently ($\leq 0.25$ pairs s$^{-1}$), and consequently, bubble detachment rarely would occur during the 100 ms interval between top and bottom readings. If detachment does occur during this interval, these outliers can be identified visually when plotted and confirmed by examination of the data. By discarding these outliers, standard deviation of the two-transducer data set can be reduced nearly tenfold relative to the single-transducer data.

Autocorrelation analysis would reduce variability of the single-transducer data in this example, but autocorrelation analysis would be less valuable for typical infiltration data because rate of bubbling changes with time, and measurement intervals may be longer than bubbling intervals. Alternatively, autocorrelation is nearly eliminated from the data by using two transducers. Additionally, a second transducer near the soil-device interface verifies that the average tension at the interface during an experiment is stable over time and oscillates around the preset
The second experiment demonstrates the performance of the device during a typical infiltration run. Figures 1.3, 1.4 and 1.5 show the data from the same infiltration run at 100 mm tension on Fruitfield coarse sand at 0.10 m$^3$/m$^3$ initial water content. Figure 1.3 shows the tension measurements from the top and bottom transducers and the tension difference between paired transducer readings. The bottom transducer, 60 mm above the soil surface, fluctuates around an average tension of 160 mm. Tension at the top transducer falls erratically from 840 to 810 mm water. The difference reflects tension change due to water outflow without bubbling fluctuations. The level of water fell less than 30 mm during this 10 minute period. If warranted, precision could be increased by taking more frequent measurements and/or by using a smaller diameter water reservoir column. Figures 1.4 and 1.5 show cumulative infiltration measured by using only the top transducer (Fig. 1.4) or by using both transducers (Fig. 1.5). Also shown are the 'best fit' Philip (1957) equations generated using the least squares technique. Measurement error is reduced when two transducers are used because bubbling-induced tension fluctuations cancel out.

An alternative method of eliminating bubbling fluctuations is the installation of a differential pressure transducer. By attaching one port of the transducer to the head space and the second port near the base of the Mariotte column, the bubbling error could be canceled physically instead of arithmetically.

The elimination of bubbling error becomes more critical at lower flow rates and higher tensions because tension change due to outflow becomes smaller while
Figure 1.3: Tension changes in a Mariotte column caused by infiltration. The tension difference between the two transducers is shown as $D$ while the tensions at the top and bottom transducers are depicted as $T$ and $B$, respectively.
Figure 1.4: Cumulative infiltration at 100-mm tension over time on a Fruitfield soil at 0.10 m$^3$/m$^3$ initial water content measured by using one pressure transducer

\[ Y = 0.003X^{0.5} + 0.0000033X \quad S_{yx} = 0.01 \text{ cm} \]
Figure 1.5: Cumulative infiltration at 100-mm tension over time on a Fruitfield soil at 0.10 m$^3$/m$^3$ initial water content measured by using the difference between two transducers.
variation due to bubbling remains constant. This results in a large and increasing coefficient of variation. In particular, infiltration equations with multiple parameters that partition the outflow, would be expected to show the greatest bubbling sensitivity in the least dominant term. For example, the two-term equations in Figures 1.4 and 1.5 show only a small difference in the $X^{0.5}$ coefficient, but nearly a twofold difference in the smaller $X$ coefficient.

In summary, the improved design for an automated tension infiltrometer is useful for a range of water tensions from 0.02 to 0.50 m and for infiltration rates of $1 \times 10^{-8}$ to $5 \times 10^{-4}$ m s$^{-1}$. A bubble tower with preset air-entry ports and a valve arrangement provides for accurate tension control and rapid tension adjustment. Interchangeable Mariotte water columns of different diameters improve precision of infiltration measurements, especially at low flow rates, by matching column volume to expected outflow. And finally, two pressure transducers and a data logger are used to automate infiltration measurements and data collection. Automatic data collection increases measurement speeds, permits measurement at shorter time intervals, improves measurement precision, and allows for more efficient data handling and analysis. Using two transducers also eliminates bubbling-induced variability in infiltration measurements.
REFERENCES


SECTION II. UNCONFINED UNSATURATED INFILTRATION MEASUREMENTS ON AN AGRICULTURAL SOIL
INTRODUCTION

Infiltration of water into soil is directly related to soil macroporosity. Macropores also are important for root growth (Wang et al., 1986) and for solute movement (Beven and Germann, 1982). Tillage and compaction, however, can alter soil macroporosity. Thus, to elucidate the effects of tillage and compaction on soil macroporosity, the rate of water infiltration into macropores was measured for different tillage and wheel traffic treatments.

While macropores have been defined in a number of ways (Luxmoore, 1981); in this study, macropores are defined as pores that empty at less than 150 mm of water tension. The capillary rise equation predicts that pores of 0.2 mm nominal diameter or larger will drain at 150 mm tension. This pore size range was selected because it covers the range of primary interest for root growth and preferential solute flow. First, secondary laterals of cereal root tips have an average diameter of approximately 0.2 mm (Hackett, 1969). A root tip growing into a pore smaller than its own diameter undergoes mechanical stress (Russell, 1977). Therefore, in a soil of moderate strength, an estimate of pores with diameter of 0.2 mm and larger should be correlated with unrestricted root extension. Second, preferential solute flow also occurs in large soil pores. Scotter (1978) calculated that significant preferential flow of both strongly and weakly adsorbed solutes could occur in continuous macropores with diameters greater than 0.2 mm.

Tension infiltrometers have been used to estimate soil pore and hydraulic properties. Clothier and White (1981) and Walker and Chong (1986) used tension infiltrometer measurements to estimate sorptivity. Moore et al. (1986) and Wil-
son and Luxmoore (1988) measured one dimensional infiltration rates on forest soils to estimate macroporosity and unsaturated hydraulic conductivity. Control of tension at the soil surface by a tension infiltrometer limits the size of pores that are conducting water (Clothier and White, 1981) and allows the measurement of unsaturated infiltration. Imposition of sequentially higher tensions leads to the incremental draining of smaller and smaller pores. Infiltration rates decrease as more of the water-conducting pores empty. Therefore, by comparing infiltration rates at increasing tensions, the relative contributions to water flow by various pore sizes can be evaluated. Greater relative water flow rates are assumed to indicate more and/or better connected pores within a pore size class. This study was conducted to determine the effects of wheel traffic and tillage on pore structure as measured by water flow through macropores.
MATERIALS AND METHODS

In this study, unconfined infiltration rates at selected tensions were measured using a tension infiltrometer. Measurement at multiple tensions allowed the evaluation of treatment effects on different pore sizes. Three-dimensional flow measurement avoids two problems inherent in one-dimensional measurement: 1) truncation or destruction of pores caused by driving a ring or isolating a soil monolith, and 2) wall flow along the edge of the soil sample.

Field plots were established in the fall of 1984 on a Tama soil (fine-silty, mixed, mesic typic Argiudoll) 12 km west of Marshalltown, IA. Corn (Zea mays L.) and soybeans (Glycine max L. Merr.) were grown in rotation on the site beginning in 1985. Corn was grown in 1988 on the areas where infiltration measurements were taken. Three tillage systems (no-till, ridge, and chisel plow) with controlled wheel traffic had been established on the site. Infiltration measurements were taken only on the no-till (NT) and chisel plow (CP) tillage systems. No-till plots received no primary tillage and were cultivated once a year. Chisel plow plots were chiseled in the fall, disked shortly before planting, and cultivated. Plots were arranged in a five-row configuration in 76 cm rows and all wheel traffic and foot traffic was confined to the same interrows throughout the year.

Infiltration measurements were made in mid-June shortly before the 1988 cultivation. Infiltration measurements were taken in four replications of the two tillage systems. Within each tillage system replication, measurements were taken at four sites, two in the middle of an interrow with wheel traffic (TRF) and two in the middle of an interrow with no wheel traffic (NOT). Each of the four combinations
of tillage and wheel traffic were measured at eight sites for a total of 32 sites. At each site, steady-state (unconfined) infiltration was measured at four tensions: 0-, 30-, 60-, and 150-mm water tension.

At each infiltration site, an area approximately 25–30 cm in diameter was cleared to a depth of 20 to 30 mm and leveled. Flow measurements were taken from low to high tension (0 to 150 mm) on a 7.62 cm diameter circular area on the cleared soil surface. To delimit the surface infiltration area, a 7.62 cm diameter ring approximately 1.5 cm high was pushed 0.5 cm into the soil. The ring was sharpened to make insertion into the soil easier. A concentric outer ring 1 cm in height acted as a depth stop for the 1.5 cm ring to attain a 0.5 cm depth when inserted into the soil.

A 7.62 cm diameter single-ring infiltrometer was used for saturated-infiltration measurements (Bouwer, 1986). The infiltrometer consisted of a Mariotte bottle equipped with a pair of pressure transducers to measure infiltration rates (Ankeny et al., 1988) and a water outlet tube placed in the infiltrometer ring to supply water to the soil surface. Several layers of cheesecloth were placed on the soil surface to reduce occlusion of macropores over the course of the measurement. Water was then ponded to a height of approximately 0.5 cm in the ring. Water was ponded on the surface for at least 15 minutes prior to the start of measurements. After prewetting, infiltration was monitored for 1000 seconds (250 measurements at 4 second intervals).

After completion of the saturated measurement, the supply tube from the Mariotte bottle was removed from the infiltrometer ring. The ring was filled with a fine
sand and leveled with a straight edge. A tension infiltrometer, preset at 30 mm tension, was then gently placed in contact with the sand. The infiltrometer was anchored by pushing four sharpened threaded rods at the corners of the base of the infiltrometer into the soil. These anchors prevented rocking of the infiltrometer by wind gusts. Recording of data began within 60 seconds after placing the device on the sand. Unsaturated infiltration was also monitored for 1000 seconds at 4 second intervals.

After recording data at 30 mm tension, the tension was increased (without moving the device) by closing the 30 mm tension port and opening the 60 mm tension port on the bubble tower of the infiltrometer. This procedure then was repeated for the 150 mm tension setting. Recording of data did not begin until the bubble tower bubbled. Bubbling indicated that the desired tension at the soil surface had been attained. The interval before bubbling at the increased tension varied from nearly zero for sites and tension settings with high infiltration rates to approximately five minutes for sites and settings with lower infiltration rates. After completion of infiltration measurements at all four tensions at a site, a 7.62 cm soil core was taken at the site of infiltration and qualitatively examined for root growth and visible macropores. The design of the experiment was a split-split plot with tillage the first split and wheel traffic the second split. Tillage and traffic were class variables and tension was used as a regression variable. Both infiltration rate and tension were log transformed to linearize their relationship.
RESULTS AND DISCUSSION

An example of unconfined infiltration data from one field site is shown in Figure 2.1. This figure shows cumulative water infiltration at four tensions into a chisel plow untrafficked interrow site. Infiltration rates are fairly constant throughout the 1000 second measurement period for all tensions. Each increase in tension causes a decrease in infiltration rate with the largest decrease in rate occurring between 0 and 30 mm tension. The rates (Table 2.1) are the slopes of the regression of infiltration versus time for the last 500 seconds of each infiltration. Mean rates varied from approximately 300 μm s⁻¹ down to approximately 2 μm s⁻¹.

Both the main effect of wheel traffic and the interaction of tillage and wheel traffic were significant (Table 2.2). Wheel-traffic reduced infiltration at all tensions in both tillages, but reduced infiltration more in the chisel plowed plots than in the no-till plots (Table 2.1). Averaged over wheel-traffic treatments, however, the main effect of tillage was not significant.

The response of infiltration rates to changes in water tension was analyzed by examining the linear regression of the natural log of infiltration rates on the natural log of tension. In general, increasing tension decreases the infiltration rate (Fig. 2.2) because increasing tension reduces the size and number of pores conducting water. The log-log transformation, initially used by Wind (1955), was effective in linearizing treatment effects. Ahuja et al. (1980) and Schuh et al. (1984) also have used a similar transformation for tensions greater than the air entry value. The largest pores observed on the infiltration surface in the field had a diameter of approximately 6 mm. Using the capillary rise equation, the calculated nominal air
Figure 2.1: Cumulative water infiltration at four tensions for a chisel-plow untraflicked interrow site on a Tama silty clay loam
Table 2.1: Summary of means and coefficients of variation for unconfined saturated and unsaturated infiltration rates into Tama silty clay loam

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Tension</th>
<th>Rate</th>
<th>CV$_{in}$</th>
<th>CV$_{mean}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm water</td>
<td>μm s$^{-1}$</td>
<td>%</td>
<td>%</td>
</tr>
<tr>
<td>Untrafficked no-till</td>
<td>0</td>
<td>232.5</td>
<td>0.56</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>53.2</td>
<td>0.28</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>31.5</td>
<td>0.33</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>9.6</td>
<td>0.69</td>
<td>35</td>
</tr>
<tr>
<td>treatment average</td>
<td>-</td>
<td>81.7</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Trafficked no-till</td>
<td>0</td>
<td>22.5</td>
<td>2.96</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>6.7</td>
<td>1.83</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>4.7</td>
<td>1.77</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>3.2</td>
<td>2.64</td>
<td>28</td>
</tr>
<tr>
<td>treatment average</td>
<td>-</td>
<td>9.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Untrafficked chisel</td>
<td>0</td>
<td>292.6</td>
<td>0.30</td>
<td>44</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>53.8</td>
<td>0.22</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>34.4</td>
<td>0.55</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>12.5</td>
<td>0.55</td>
<td>28</td>
</tr>
<tr>
<td>treatment average</td>
<td>-</td>
<td>98.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Trafficked chisel</td>
<td>0</td>
<td>9.4</td>
<td>7.01</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>4.4</td>
<td>4.15</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>2.9</td>
<td>4.14</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>2.2</td>
<td>3.65</td>
<td>32</td>
</tr>
<tr>
<td>treatment average</td>
<td>-</td>
<td>4.7</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 2.2: Mean squares from the analysis of infiltration data from unconfined infiltration into a silty clay loam soil for natural-log transformed infiltration rates and tensions

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>df</th>
<th>MS</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rep</td>
<td>3</td>
<td>0.0108</td>
<td>0.66 ns</td>
</tr>
<tr>
<td>Tillage (Till)</td>
<td>1</td>
<td>0.1072</td>
<td>6.52 ns</td>
</tr>
<tr>
<td>Error A</td>
<td>3</td>
<td>0.0164</td>
<td>-</td>
</tr>
<tr>
<td>Traffic (Trf)</td>
<td>1</td>
<td>14.786</td>
<td>219. **</td>
</tr>
<tr>
<td>Tillage x Traffic</td>
<td>1</td>
<td>0.4681</td>
<td>6.96 *</td>
</tr>
<tr>
<td>Error B</td>
<td>6</td>
<td>0.0673</td>
<td>-</td>
</tr>
<tr>
<td>Tension_{in}</td>
<td>1</td>
<td>8.6529</td>
<td>1,055 **</td>
</tr>
<tr>
<td>Tension_{of}</td>
<td>2</td>
<td>0.0565</td>
<td>0.70 ns</td>
</tr>
<tr>
<td>Tension_{in} x Till</td>
<td>1</td>
<td>0.2944</td>
<td>35.9 **</td>
</tr>
<tr>
<td>Tension_{of} x Till</td>
<td>2</td>
<td>0.0028</td>
<td>0.34 ns</td>
</tr>
<tr>
<td>Tension_{in} x Trf</td>
<td>1</td>
<td>0.7877</td>
<td>96.1 **</td>
</tr>
<tr>
<td>Tension_{of} x Trf</td>
<td>2</td>
<td>0.0384</td>
<td>4.68 *</td>
</tr>
<tr>
<td>Tension_{in} x Trf x Till</td>
<td>1</td>
<td>0.0344</td>
<td>4.20 *</td>
</tr>
<tr>
<td>Tension_{of} x Trf x Till</td>
<td>2</td>
<td>0.0078</td>
<td>0.95 ns</td>
</tr>
<tr>
<td>Error (residual)</td>
<td>36</td>
<td>0.0082</td>
<td>-</td>
</tr>
</tbody>
</table>

* Significant at 0.05 level.

** Significant at 0.01 level.
Figure 2.2: Plot of the natural log of the unconfined infiltration rate means versus the natural log of tension for traffic and tillage combinations on a Tama silty clay loam.
entry value for a 6 mm diameter pore is 5 mm water tension. This value was used in place of zero for the log transformation of tension. The linearity obtained by the log-log transformation indicates that the relationship between infiltration and tension can be expressed in the form: $Y = ax^b$ where $y =$ infiltration rate and $x =$ tension. ‘Ln a’ and ‘b’ are the intercept and slope, respectively, of the linear regression equation for the log-log transformed data. Because infiltration rates decrease with increasing tensions, the ‘b’ slopes are negative.

The significant interaction between wheel traffic and the linear component of the sums of squares for log tension (tension$_{ln}$) in Table 2.2 indicates that wheel traffic altered the pore structure. Infiltration rates in untrafficked rows had greater decreases with increasing tension than infiltration rates in trafficked interrows (Fig. 2.2). Apparently, larger pores (i.e., those that drain at lower tensions) were conducting a greater percentage of water in untrafficked interrows than in trafficked interrows. Therefore, wheel traffic preferentially destroyed and/or prevented the formation of the large macropores that would conduct water at tensions of less than 150 mm water tension. Although infiltration rates declined more rapidly with increased tension in untrafficked sites, the absolute rate was still higher than in trafficked sites. Thus, while traffic reduced the number of water-conducting pores at all measured tensions, traffic destroyed a smaller percentage of the smaller water-conducting pores and a larger percentage of the larger pores. Culley et al. (1987) reported saturated hydraulic conductivity values of ‘undisturbed’ cores from both trafficked and untrafficked interrows on both a conventional tillage and a no-tillage treatment. They obtained the same saturated flow treatment ranking as this experiment. The
highest flow rates were in the conventionally tilled untrafficked interrows, followed by the untrafficked no-till interrows, followed by trafficked no-till interrows. The trafficked conventionally tilled interrows had the smallest infiltration rates in both studies.

Lastly, the interaction between wheel traffic and tillage and tension also was significant (Table 2.2). Trafficked interrows in no-till had greater decreases in infiltration rates with increased tension than trafficked interrows in chisel-plow plots. This data indicates that larger pores were conducting relatively more water in tracked interrows in no-till plots than in chisel-plow plots. Both tillage systems had been cultivated for weed control in the previous summer, but the chisel plow treatment also was chisel plowed in the fall and disked before planting. Wheel traffic at planting caused deeper ruts in chisel plowed interrows than in no-till interrows. Neither tillage treatment was disturbed between planting and the infiltration measurements. Thus, the reduction in large water-conducting pores in the tracked interrows of the chisel plow treatment probably resulted from greater soil compaction by wheel traffic of the tilled soil than of the untilled soil at planting. Culley et al. (1987) reached the same conclusion on a more poorly drained soil.

Some interesting nonsteady-state infiltration features also were noted during infiltration measurements. During prewetting, saturated infiltration showed a fast initial infiltration rate into dry soil that slowed to an apparent steady-state rate in approximately 5 to 10 minutes. Switching to a higher tension on the tension infiltrometer always resulted in an initial infiltration rate that was slower than the final steady-state rate as water drained from the soil.
Visual observations of macroporosity (primarily root channels with some wormholes and cracks) related well to observed infiltration rates. Roots were just beginning to reach the middle of the interrow when measurements were made. In general, soil samples with many roots had higher infiltration rates and lower bulk densities than samples with few roots. The sample with the most roots, however, had a fairly low infiltration rate. The apparent reason was that the macropores were filled with roots. This observation suggests that changes in water infiltration patterns through macropores caused by root occlusion over a growing season may be important. If these changes are large, then both sampling schemes and infiltration models may need to account for this temporal variation in infiltration.

There are two sources of error in the estimation of steady-state infiltration rates (Elrick et al., 1988): 1) not reaching a final steady-state rate, and 2) errors in rate measurement (instrument error). Coefficients of variation (CV’s) were calculated for each individual estimate of infiltration rate by dividing 100 times the standard error of the rate estimate by the rate estimate. ‘CV\textsubscript{in}’ is simply the average individual CV for a specified treatment (Table 2.1). If it is assumed that steady state flow has been attained, then CV\textsubscript{in} (e.g., the ‘noise’ around each line in Fig. 2.1) is primarily instrument error. ‘CV\textsubscript{mean}’ is calculated by dividing 100 times the standard error of the mean estimate by the mean of the eight infiltration rates measured for a given tension and treatment combination. Relative to variability among sites treated alike (CV\textsubscript{mean}), even a 7% maximum measurement error (from CV\textsubscript{in}) is adequate precision for field measurements.

Elrick et al. (1988) suggested, based on a simulated flow, that the approach to a
steady-state infiltration rate for a well permeameter may take less than 30 minutes in a permeable soil, but could require 6 hours or more in a slowly permeable soil. We determined infiltration rates for time subsets of each infiltration run to see if rates were still decreasing with time. The rate obtained from the 500 to 750 second data subset was compared to the rate from the 750–1000 second subset. Only the tracked sites at zero tension showed a rate decrease that could be detected over measurement error indicating that saturated infiltration rates of tracked sites were overestimated. Longer prewetting of less permeable sites would seem necessary to obtain more accurate steady-state rates.

Wilson and Luxmoore (1988) suggested that the variability of infiltration rates did not decrease at higher tensions. They concluded that the smaller macropores are as variable as larger pores. This is inconsistent with the conclusions of Clothier and White (1981). Errors in rate measurement, however, were not estimated in these studies. Therefore, with rate measurement variability and site variability unseparated, it is difficult to determine the cause of variation in infiltration rates when comparing pore size classes. While this experiment was not designed to measure field variability, infiltration variation due to sites is approximately an order of magnitude larger than variation due to imprecision in a rate estimate ($CV_{in}$). $CV_{mean}$'s tend to decrease with tension while $CV_{in}$'s are fairly stable across tensions for a given treatment.
CONCLUSIONS

Unconfined infiltration measurements proved useful in quantifying the effects of tillage systems and compaction on soil structure. The methods are capable of measuring infiltration across the tension range of primary interest for root growth and preferential solute movement. Separation of measurement error from experimental error allows comparisons of variability and should improve the efficiency of future experiments.

Tillage had little effect on infiltration rates, per se. Wheel traffic greatly reduced infiltration in both tillages. The chisel plow tillage, however, was more susceptible to compaction than no-till. Compaction destroys a larger percentage of pores carrying water at low tension (large pores) than of smaller pores carrying water at higher tensions. Wheel traffic at planting caused compaction that overcame any soil loosening from tillage.
REFERENCES


University, Las Cruces, NM.


SECTION III. MODELING OF ONE-DIMENSIONAL UNSATURATED INFILTRATION
INRODUCTION

Infiltration is the process of water entry into the soil. This process is affected by intrinsic soil properties as well as by management of the soil. The rate of infiltration affects solute movement, runoff, and soil erosion. Therefore, knowledge of the infiltration process is important for efficient soil and water management (Hillel, 1980).

The most straightforward way of studying unsaturated infiltration is in a simple soil system. A simple soil system is defined as a system in which moisture content and structure are initially uniform with depth and in which structure does not change during infiltration (Bond and Collis-George, 1981a). Bond and Collis-George (1981a,b) reported that little accurate experimental data existed for saturated infiltration into a simple soil system and that conflicting descriptions of the phenomena involved in infiltration have been suggested. Even less experimental data exist for unsaturated infiltration.

Water flow or flux in soil is a function of soil hydraulic potential. Hydraulic potential \((H)\) is the sum of gravitational \((H_g)\), matric \((H_m)\), and pressure \((H_p)\) potentials. The hydraulic gradient \(\frac{dH}{dz}\) is the driving force that causes water flow in soil. The distance \(z\) can be considered the distance from the point of water application, i.e., the surface in this case, to the boundary of the wetting soil with drier soil in either the horizontal or vertical dimension. Specifically, water flows downward in a gravitational field due to a gravitational potential gradient and water flows from 'wet' to 'dry' due to a matric potential gradient. The matric potential is caused by absorptive forces on particle surfaces and by capillary forces.
due to surface tension. This relationship between water flux (Q) and hydraulic potential gradient (dH/dz) is formalized by Darcy's law as:

$$Q = K(H_m) \times \left( \frac{dH}{dz} \right)$$

where 'K', the hydraulic conductivity of the soil, varies greatly with the water potential (Hm) applied to the soil. This variation in soil hydraulic conductivity makes measurements and solutions of practical water flow problems difficult.

Sorptivity (S) embodies in a single parameter the influence of matric potential and hydraulic conductivity on transient flow (or wetting) processes (Hillel, 1982). The value of sorptivity is therefore dependent upon initial and imposed water potentials. The driving force for sorptivity is the matric potential gradient. The drier the soil at the start of infiltration, the greater the sorptivity. For horizontal infiltration (I),

$$I = S \times t^{0.5}$$

describes water flow as a function of time (t) with great accuracy. Horizontal infiltration is linear with the square root of time.

If there is no matric potential gradient (i.e., uniform soil water potential throughout the soil volume, dHm/dz=0), water flux is equal in value to the hydraulic conductivity (K) because the only driving force is gravity (dHg/dz=1 for gravitational potential gradient). Infiltration (I) is described simply as:

$$I = K \times \frac{dH}{dz} \times t = K \times t$$

For downward water flow into dry soil, both gravitational and matric potentials are important. Separating contributions of the two driving forces to water flux is
difficult because they interact. No exact practical solution currently exists. The most popular approach is to use the two-term Philip equation which uses the first two terms of an infinite series expansion and assumes a homogeneous soil (Philip, 1957a).

\[ I = S_{ph} t^{0.5} + A_{ph} t \]

'S_{ph}' is sorptivity calculated from the Philip equation. 'A_{ph}' is the first term of an infinite series. Subsequent terms are ignored in the two-term simplification. Researchers often equate A_{ph} from the Philip equation with K. Unfortunately, this equation is an oversimplification of water flow. Negative values of A_{ph} (which implies that water flows against the gravitational gradient, i.e., 'uphill') are often obtained (Fahad et al., 1982). One paper (Davidoff and Selim, 1986) used eight different equations to estimate infiltration parameters. Although empirical equations may fit the data well, they do little to describe the physics of water infiltration.

When water is applied to soil, the wetting front advances faster vertically than horizontally because both matric and gravitational potential act vertically while only matric potential acts horizontally. Therefore, the distance of water movement from the point of water application on the surface to the wetting front below is a longer distance than to the wetting front on the surface. If distance \( z \) to the wetting front is increased downward, then the matric gradient, \( \frac{dH_m}{dz} \), is less vertically than it is laterally at any given time. Therefore, the gravitational potential gradient and gravitational water flow reduces the matric potential gradient and matric flow. While infiltration driven by the matric potential gradient ('sorptivity' flow), is proportional to the square root of time in horizontal flow, this gradient
is smaller for vertical flow. Therefore, sorptivity flow downward must accumulate more slowly than the square root of time because of the diminished driving gradient. Thus, the square root of time dependency of the sorptivity term in Philip's equation is physically incorrect for downward infiltration. The dependence of downward infiltration on both a linear (gravity) and a nonlinear (decaying matric potential gradient) process makes it difficult to model water flow in soil.

A new 'simple' nonlinear infiltration model, proposed by Swartzendruber (1987) has a better form to describe infiltration because the contribution of sorptivity diminishes faster than the square root of time.

\[ I = \left( \frac{S_{sw}}{A_{sw}} \right) \left( 1 - e^{-A_{sw} \times t^{0.5}} \right) + (K_{sw} \times t) \]

or its time derivative:

\[ \frac{dI}{dt} = 0.5 \times S_{sw} \times t^{-0.5} \times e^{-A_{sw} \times t^{0.5}} + K_{sw} \]

This equation provides a single mathematical form for soil water infiltration for all times greater than zero. \( A_{sw} \), in this equation has no direct relationship to the \( A_{ph} \) of the Philip equation. The form is exactly integrable, thus providing a generally applicable single equation for either cumulative quantity of water infiltrated or rate of infiltration, both as functions of time (Swartzendruber, 1987).

The focus on gravity and capillary potential in water movement in the discussion above suggests that these are the only major factors in water infiltration into soil. Air flow, however, has also been demonstrated to be important in water movement (Bond and Collis-George, 1981a). As water infiltrates into soil, some air is trapped in pores, because air escape routes are cut off by fingers of the advancing
wetting front. If wetting is slow, small pores fill before large pores and less air is trapped in small pores. If wetting is fast, larger pores fill sooner and can result in more encapsulated air in the soil. Therefore, initial water content and the rate at which water is applied affects the degree of soil wetting and the measured infiltration rate. While some air is trapped, most of the air moves out of the pores as water displaces the air. This displacement of air at the wetting front causes an increase in air pressure (a 'backpressure') large enough to decrease infiltration rates at short times (Collis-George and Bond, 1981). This also means that the air encapsulated in the pores is pressurized. This air will then dissolve into the percolating water over time and conductivity of that soil will then increase over the course of the infiltration.

Separating contributions of matric and gravitational potentials to water flow would have some practical advantages. Sorptivity is dependent upon initial and final soil water content. Therefore, changes in sorptivity can be related to changes in the soil water content from one tension or pore size to another. Hydraulic conductivity is more dependent upon pore continuity. If sorptivity and conductivity are measured at a series of tensions where various pores are filled or emptied of water, then sorptivity and conductivity can be used to estimate pore volume, size, and continuity. Thus, soil structure could be described in terms of sorptivity and conductivity estimates obtained from infiltration measurements.

Because of technical difficulties, such as poor measurement precision, very few measurements of unsaturated infiltration at controlled tensions have been made. While technical and modeling problems are not simple, improved understanding
of soil structure is needed for improved crop, soil and water management. The availability of a tension infiltrometer to obtain data and of a physically meaningful equation to obtain needed parameters made this problem appear tractable.

The objectives of this work were to determine if unsaturated hydraulic conductivity and sorptivity in soil cores could be obtained from one infiltration measurement. By varying the initial water content of the soil cores and by varying the tension that water was applied to cores, a set of sorptivities and conductivities for a particular soil can be calculated using the two infiltration equations discussed. If calculated hydraulic parameters were consistent with independently measured water contents and hydraulic conductivities at different tensions, then calculated parameters could be used in a model of soil structure.
MATERIALS AND METHODS

Fruitfield sand was used for infiltration measurements at constant tension (100 mm water) and varied initial soil water contents. Infiltration measurements were taken using a tension infiltrometer. Unit gradient measurements (discussed below) were also taken to determine the unsaturated hydraulic conductivity. Air-dry Fruitfield coarse sand (sandy, mixed, mesic Entic Hapludoll) was hand-packed to a bulk density of $1.60 \pm 0.02 \text{ Mg/m}^3$ in 7.62 cm diameter clear acrylic rings. Twelve 2-mm holes were drilled in each 5 cm high acrylic ring to allow air escape during infiltration. Water was then added to obtain the final water content (0.0-, 0.05-, and 0.10-$\text{m}^3/\text{m}^3$) and allowed to equilibrate. Because unsaturated hydraulic conductivity of coarse sand varies greatly over small tension changes, it was not used for measurements of different initial tensions applied by a tension infiltrometer. Six to eight replications were used for infiltration and unit gradient measurements.

A second soil, an Ida silt loam was used for measurements of varied applied tensions and fixed initial water content (air-dry). Both infiltration and unit gradient measurements were taken at 50-, 100-, and 200-mm water tension. Ida soil (coarse, silty, mixed, mesic typic Udorthent) was hand-packed to a bulk density of $1.15 \pm 0.02 \text{ Mg/m}^3$. The same acrylic rings used for Fruitfield soil were used for Ida soil. Eight replications were used for infiltration and unit gradient measurements.

Steady-state unsaturated unit gradient infiltration rates were obtained by using a Mariotte system to provide water to the soil surface at the desired tension through a porous membrane. The tension at the top of the core was matched at the bottom of the soil core by using a hanging water column. Unit gradient measurement means
that hydraulic potential gradient is equal to one and the soil is at a uniform matric potential. Gravity is the sole driving force. The unit gradient technique provides the most direct measurement of unsaturated hydraulic conductivity. The method is discussed in detail by Klute and Dirksen (1986). Outflow over time was measured by collection in graduated cylinders. Infiltration measurements also were made using the tension infiltrometer and procedures of Ankeny et al. (1988) described in the first section of this dissertation.
RESULTS AND DISCUSSION

Fruitfield coarse sand was used in the first experiment. Infiltration was measured at 10 cm of water tension. The initial amount of water added to the soil cores varied from 0.0 to 0.10 m³/m². The estimate of hydraulic conductivity obtained from unit gradient measurements \((K_{ug})\) was 0.278 \(\mu\)m s⁻¹. The values of \(K_{sw}\) from the Swartzendruber analysis (Table 3.1) ranged from 0.197 \(\mu\)m s⁻¹ at 0.10 added water to 0.23 \(\mu\)m s⁻¹ at 0.05 m³/m³ water content. These values of \(K_{sw}\) are consistent and close to the unit gradient estimate of 0.278 \(\mu\)m s⁻¹ even though initial water content varied. The rate of flow during the unit gradient measurement generally increased for several hours before reaching a steady rate. One explanation is that small amounts of air in the soil cores continued to dissolve over several hours. If this is true, then the unit gradient value \((K_{ug})\) would be expected to be slightly larger than \(K_{sw}\). The values of \(A_{ph}\) from the second term of the two-term Philip equation showed the pattern expected from Philip's theory. Philip (1957b) showed that the value of \(A_{ph}\) in the two term equation increases as initial water content increases. This is reflected in estimates of Philip's \(A_{ph}\) (Table 3.1). \(A_{ph}\) is most negative at 0.0 m³/m³ initial water content and becomes less negative as initial water content increases. Both theoretically and practically, the two-term equation, although popular, is inadequate for describing the physics of water infiltration because values of \(A_{ph}\) are negative and are not constant as initial water content increases. Swartzendruber's equation gives an estimate of hydraulic conductivity that is consistent with the unit gradient estimate of hydraulic conductivity in this sandy soil and does not change much with initial water content. An accurate
Table 3.1: Infiltration parameters derived using the Swartzendruber and Philip equation from cumulative water infiltration data for Fruitfield soil cores at varying initial water contents

<table>
<thead>
<tr>
<th>Water content (m^3/m^3)</th>
<th>Swartzendruber equation</th>
<th>Unit gradient rate</th>
<th>Philip equation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S_{sw}</td>
<td>SE</td>
<td>A_{sw}</td>
</tr>
<tr>
<td>0.00</td>
<td>79.300</td>
<td>16.627</td>
<td>0.026</td>
</tr>
<tr>
<td>0.05</td>
<td>29.098</td>
<td>9.484</td>
<td>0.011</td>
</tr>
<tr>
<td>0.10</td>
<td>40.782</td>
<td>16.579</td>
<td>0.030</td>
</tr>
<tr>
<td></td>
<td>K_{ug}</td>
<td>SE</td>
<td>S_{ph}</td>
</tr>
<tr>
<td>0.00</td>
<td>-</td>
<td>-</td>
<td>71.100</td>
</tr>
<tr>
<td>0.05</td>
<td>-</td>
<td>-</td>
<td>38.127</td>
</tr>
<tr>
<td>0.10</td>
<td>-</td>
<td>-</td>
<td>26.407</td>
</tr>
<tr>
<td>0.165</td>
<td>0.278</td>
<td>0.008</td>
<td>-</td>
</tr>
</tbody>
</table>
method to estimate hydraulic conductivity, independent of initial water content, would be a useful tool for characterization of an important soil property.

The other parameter the two models share is sorptivity (S). The sorptivity values obtained from the Philip equation \( S_{ph} \) decreased with increasing initial water content (Table 3.1). Values of S obtained from Swartzendruber's equation \( S_{sw} \) did not consistently decrease with increasing volumetric water content. Sorptivity should decrease with increasing initial water content, but the calculated average value of \( S_{sw} \) at 0.10 m³/m³ initial water content was less than the value of \( S_{sw} \) at 0.05 m³/m³ added water. Therefore, the Philip two-term equation gave a more precise estimate of sorptivity. One explanation for poorer performance of the Swartzendruber equation is that non-linear equations do not always yield a unique solution. Therefore, there may not be a unique solution for the parameters. A second possible explanation is that effects of both \( S_{sw} \) and \( A_{sw} \) on infiltration are at a maximum at early times. Measurement error is also at a maximum because of small errors in determining the exact beginning of infiltration (time = 0) due to the time required to establish contact between the tension infiltrometer and the soil surface. Reducing the number of parameters in an equation can often stabilize parameter estimates in nonlinear equations. When data sets were analyzed with a fixed \( A_{sw} \) value, reasonable values of both \( S_{sw} \) and \( K_{sw} \) were usually obtained. No \textit{a priori} justification to fix the value of \( A_{sw} \) could be found, however. Therefore, this approach was discarded. Air flow was not considered in these analyses.

Ida silt was used for infiltration measurements at constant initial water content and varied initial applied water tensions. The change in hydraulic conductivity of
the Ida soil was less than that of Fruitfield soil over the 50 to 200 mm tension range which made it possible to use cores of reasonable length in the laboratory. As tension increased, the value of $A_{ph}$ increased (Table 3.2).

The increase in $A_{ph}$ with tension is in contrast with the decrease in unit gradient measurements with increasing tension. $K_{sw}$ consistently overestimated unsaturated hydraulic conductivity as measured by steady-state rate but did not show a pattern consistent with increasing tension or decreasing unit gradient rates. This overestimation of conductivity in Ida soil was inconsistent with the Fruitfield results and unexpected. Various manipulations of Swartzendruber's equation did not change the overestimate of the 'true' $K$.

Values of $S$ from both Swartzendruber and Philip analysis gave results consistent with physical expectations in that $S$ decreased with increasing tension of applied water. As expected, the values of $S_{sw}$ were larger than that of $S_{ph}$. The calculation of $S$ in the Swartzendruber equation 'weights' later time points less than does the Philip equation because the matric potential gradient is discounted at later times. This means that $S$ is not underestimated in the Swartzendruber equation due to the overestimate of the matric potential gradient that occurs in the two-term Philip equation.

The results of these experiments, in light of the results of Bond and Collis-George (1981a) suggest that pore air pressure at the wetting front influenced infiltration events and subsequent analysis of the data. In their second paper, Collis-George and Bond, (1981) predicted that coarser materials and better venting of the wetting front to the atmosphere will reduce effects of air pressure. Air pressure at
Table 3.2: Infiltration parameters derived using the Swartzendruber and Philip equation from cumulative water infiltration data for Ida soil cores at different applied water tensions

<table>
<thead>
<tr>
<th>water tension (mm)</th>
<th>$S_{sw}$</th>
<th>SE</th>
<th>$A_{sw}$</th>
<th>SE</th>
<th>$K_{sw}$</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>1930.000</td>
<td>198.658</td>
<td>0.050</td>
<td>0.007</td>
<td>19.633</td>
<td>1.192</td>
</tr>
<tr>
<td>100</td>
<td>1362.500</td>
<td>163.745</td>
<td>0.012</td>
<td>0.006</td>
<td>8.605</td>
<td>1.589</td>
</tr>
<tr>
<td>200</td>
<td>1095.000</td>
<td>167.662</td>
<td>0.025</td>
<td>0.013</td>
<td>11.151</td>
<td>1.916</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>water tension (mm)</th>
<th>$K_{ug}$</th>
<th>SE</th>
<th>$S_{ph}$</th>
<th>SE</th>
<th>$A_{ph}$</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>4.260</td>
<td>0.135</td>
<td>1490.000</td>
<td>143.589</td>
<td>-0.147</td>
<td>0.875</td>
</tr>
<tr>
<td>100</td>
<td>3.951</td>
<td>0.115</td>
<td>1356.250</td>
<td>119.994</td>
<td>-1.096</td>
<td>0.449</td>
</tr>
<tr>
<td>200</td>
<td>2.429</td>
<td>0.361</td>
<td>846.250</td>
<td>103.405</td>
<td>-2.628</td>
<td>0.464</td>
</tr>
</tbody>
</table>
the wetting front should reduce infiltration of Fruitfield soil less than that of the finer (silty) Ida soil. If water is infiltrating into soil and displacing air, then there must be a greater than atmospheric pressure at the wetting front. The pressure buildup will be most pronounced where flow rates are high and conducting pores are small. In this study, maximum air flow occurs when water flow is also at a maximum, i.e., early infiltration. Because sorptivity is the most dominant parameter at early times, this leads to an underestimate of 'true' sorptivity. Also, partitioning the obtained infiltration into sorptivity- and conductivity-derived flux using least squares analysis necessarily would result in more flux being partitioned into the linear (conductivity) component. This may explain why $K_{sw}$ is larger than $K_{ug}$ in the Ida soil.
CONCLUSIONS

Both models tested on the infiltration data were shown to have limitations in characterization of soil hydraulic parameters. The Philip two-term infiltration model did not yield a physically reasonable (i.e., positive) hydraulic conductivity. The Swartzendruber model generally gives reasonable values of K, but yields more variable estimates of S. Neither model considers air flow in the infiltration event. More knowledge of air flow would be needed to physically understand water flow in these studies. The Swartzendruber model appears potentially useful for estimating hydraulic conductivity of unsaturated soils.
REFERENCES


SUMMARY AND CONCLUSIONS

The improved tension infiltrometer design provides tension control and measurement precision necessary for laboratory and field measurements of unsaturated infiltration rates. The critical design improvement incorporated into the device is use of a pair of transducers. This improvement eliminates most measurement 'noise' associated with bubbling in Mariotte reservoirs. Reduced 'noise' reduces measurement variability, which extends the practical range of the device to higher tensions and lower flow rates. The infiltrometer performed well in field and in laboratory studies.

Major findings of the field study were: 1) wheel traffic reduced infiltration rates in both no-till and chisel-plow tillage systems, 2) increasing tensions lead to decreasing infiltration rates in tillage and in traffic treatments, 3) larger pores were preferentially destroyed by wheel traffic, and 4) the chisel-plow tillage was more susceptible to compaction by wheel traffic than was the no-till.

Air backpressure probably reduced infiltration rates and adversely affected performance of the two models which ignored backpressure. Swartzendruber's equation gave reasonable estimates of hydraulic conductivity and variable estimates of sorptivity on Fruitfield soil. The two-term Philip equation gave consistent estimates of sorptivity. Backpressure from air movement in the Ida soil appeared to invalidate
physical assumptions of the equations used. Use of steady-state infiltration rates avoids some of the difficulties of modeling changes in infiltration rates. Unconfined rates are quite constant and only one parameter need be calculated versus two or three in the selected infiltration equations.

Unsaturated infiltration measurements, albeit with more intensive labor, show many of the same trends as soil strength and bulk density measurements. If cultivars or fertility treatments are the focus of a study with fairly uniform soil management, then soil parameters of choice might be strength or bulk density because of the relative speed and simplicity of measurement. Information from unsaturated infiltration measurements, however, may be more desirable where knowledge of soil pore structure is important or where destructive sampling must be avoided. Knowledge of pore structure is of paramount importance in the processes of solute movement and saturated and unsaturated infiltration. Infiltration measurements are directly applicable to these processes and provide an indirect measurement of soil structure.

Because roots tend to grow in pores rather than randomly through the soil matrix, information from pore property measurements should be better than bulk property measurements (e.g., bulk density or soil strength) in characterizing tillage and compaction effects on root growth. Therefore, more research is needed to determine if unsaturated infiltration measurements are a pore way to quantify soil tilth.

Further modifications of the tension infiltrometer should increase potential applications. When the bubbling tube is inserted into the top instead of the bottom of the Mariotte column, infiltration into the soil occurs at a continuously increasing
tension. Tension and cumulative infiltration are linearly linked in this configuration of the tension infiltrometer. Therefore, infiltration rate data can be gathered at multiple tensions from one setup of the device. Infiltration rate can be directly related to the corresponding tension at a given time. Thereby, a description of the soil hydraulic properties is obtained. Further theoretical development may lead to a physical interpretation of what this description might mean.

The tension infiltrometer is a specialized device that can measure a narrow range of tensions and infiltration rates. Nonetheless, this narrow range of infiltration rates is of practical importance. Hamblin (1985) compares various rainfall rates to the rates required for saturated water flow in various soil types. For example, she estimates a heavy rain of 20 mm/hour is required to initiate saturated infiltration in a silt loam. A light rain of 5 mm/hour is required to initiate saturated infiltration (i.e., water-filled macropores) in a sandy clay. Macropore flow is dependent on soil hydraulic potential and soil hydraulic potential is dependent on soil type and on rainfall intensity. Where rainfall rates are variable, (e.g., Iowa with summer cloudbursts and gentler spring rains), the occurrence of macropore flow and solute leaching depends on both rainfall intensity and soil type. The literature is replete with acknowledgments of the importance of macropores and of macropore flow, but the process controlling macropore infiltration rates, i.e., rainfall intensity (or in its stead, an infiltrometer), is often ignored in macropore experiments. When water is ponded on the soil surface, soil pores control the infiltration process, whereas, normally the infiltration (rainfall) process controls which soil pores conduct water and solutes. The control of tension in the tension infiltrometer allows a modulation
of macropore flow that should prove useful in some solute studies.

Soil physics theory does not yet have a useful general model to predict water infiltration and subsequent water and solute redistribution in the field. Nor does empirical data gathered to monitor water infiltration, content, and quality adequately explain the processes of water and solute flow in the field. I believe that part of the solution to these limitations is to consider water infiltration processes that are often ignored.

Three such infiltration processes are variations in rainfall intensity (discussed above), the influence of crop architecture on infiltration, and the effects of root growth on water infiltration and redistribution. A corn crop with a leaf area index of four or five will intercept and direct a large proportion of incident rainfall down the stem to the center of root-containing macropores. Infiltration rates will vary dramatically on a small scale. This will influence the degree of local soil wetting and solute movement. Root growth itself affects infiltration rates and soil structure as roots grow through the soil, proliferate, die, and decay. Rainfall intensity, crop architecture, root growth, tillage, and soil type are variables and processes in all field experiments. While it is easy to develop an argument for the importance of these factors, it is more difficult to measure their effects. The author hopes the methods developed here will be useful in the work of understanding a few of the complex relationships of root growth, soil structure, tillage, and water and solute movement in the soil.
LITERATURE CITED


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