The Influence of Soil Textural Stratification and Compaction on Moisture Flow

J. R. EAGLEMAN AND V. C. JAMISON

ABSTRACT

Knowledge of the water transporting properties from one soil layer to another is important because of the difference of soils in the field. The purpose of this study was to determine the characteristics of moisture flow at the plane of contact of soil layers differing in texture, structure, and compaction.

Measurements of the velocity of flow and hydraulic gradients were obtained in the suction range of zero to seven hundred cm of water by using a laboratory model. Three different textural pairs were used. Two pairs, Salix silt loam with a fine sandy loam overwash and a Salix silt loam with an overburden of sandy loam, were sampled from naturally occurring textural breaks in alluvial soil profiles.

Hydraulic conductivity measurements across the textural breaks showed that moisture was readily transferred from the large to small pores, but that a barrier existed for water movement from small to large pores. In the naturally occurring breaks in soil texture, it was found that the compaction of the different soil layers determined the degree of expression of the barrier to water movement.

CONTENTS

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INTRODUCTION

The increasing crop yields due to heavy fertilizer applications are placing greater demands upon other soil properties such as moisture transfer within the soil. Since plant growth is dependent upon a moisture supply, it is important to know the factors which influence the capacity of soil to supply moisture to plant roots. The movement of water within is important since the original supply is at the surface of the soil and the plant roots are at some depth beneath the surface. The mobility of the soil water is even more important if the moisture moves by gravity and other forces from the surface down past the root zone and returns to the plant roots by capillary action and distillation.

There are very few soils in the field which have uniform texture and structure throughout. Since the soil water must move through the pore spaces of the soil, it seems reasonable that a change in texture or structure will be accompanied by a change in water transporting properties. These changes are the basis of this investigation.

The purpose of this study was to determine the water transporting properties existing at the plane of contact made by layers of soil differing in texture, structure, and compaction. These properties were studied from measurements of the hydraulic gradient, and velocity of flow obtained at the plane of contact of the different soil materials.

LITERATURE REVIEW

Darcy (3)* was one of the first workers to show that the flow of water through a porous medium could be described and predicted by an equation relating the driving force present to the movement of water under saturated conditions. The present form of his equation is,

$$V = Ki$$

Where:

V is the volume of water passing a unit cross sectional area perpendicular to the line of flow per unit time.
K is the hydraulic conductivity.
i is the driving force per unit length of the soil column.

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*Numbers refer to a list of references in the back of this bulletin.

The K value in Darcy's equation was originally intended to be a coefficient which was obtained under saturated conditions and was related to the particular soil material used. Later investigators (5, 6, 7, 9) have shown that the hydraulic conductivity can be used as an expression of water movement in the unsaturated state, but that its value under these conditions will depend upon the moisture content as well as the soil or other porous system used. Several unsaturated flow equations have been proposed (4, 6, 7, 8) but their usefulness has been limited to special cases.

In addition to the influence of the moisture content upon saturated flow, various workers have reported other factors which affect the unsaturated flow of moisture through a porous medium. The basic forces responsible for the movement of soil water (2) are gravity, hydraulic pressure, osmotic pressure, and the adhesion of water to the solid surfaces.

Water movement through six different layers of soil has been studied (1). It was found that each layer of soil held the same amount of water regardless of its position in the column except when it occurred above a layer of coarse sand. All such layers underlain by sand held more water than when the sand layer was absent or located above them.

MATERIALS, EQUIPMENT, AND PROCEDURE

The purpose of this study was to determine the moisture flow characteristics from one soil layer to another. Measurements were obtained on three pairs of soil materials which were placed in a laboratory model one pair at one time. Distilled water was used to saturate the soils. Daily moisture measurements were taken for about a month after saturation.

THE SOILS. Three different pairs of soil materials were used. The first pair was a graded sand in contact with a loessal derived silt loam. The diameters of the sand grains used ranged between 250 and 300 microns. The silt loam was obtained from the subsoil of a Menfro silt loam profile. The particle size distribution obtained by the hydrometer method showed that the silt loam was composed of 15.0 percent sand, 55.5 percent coarse silt, 16.5 percent fine silt, and 13.0 percent clay.

The second pair of soil materials used was sampled from an alluvial Salix silt loam with a fine sandy loam overwash located on the Southeast Missouri Research Center near Portageville. The texture of the upper ten inches of the profile was fine sandy loam with an abrupt

break to silt loam at ten inches. The particle size distribution as determined by the hydrometer and wet sieve methods is shown in Table I. Bulk density samples taken with the Uhland sampler were determined to contain 1.63 gms/cc in the fine sandy loam and 1.37 gms/cc in the silt loam. X-ray diffraction patterns indicated that the clay minerals in both the fine sandy loam and the silt loam were composed of montmorillonite, kaolinite, and illite.

The third pair of soil materials used was obtained from a Salix silt loam profile which had an overburden of sandy loam placed over it by leveling operations. This soil was also located on the Southeast Missouri Research Center near Portageville. The texture of the upper 8 1/2 inches of the profile was a sandy loam with an abrupt break into silt loam. The same initial determinations were made on this soil as was made on the Salix silt loam with a fine sandy loam overwash. The particle size distribution is shown in Table I. The bulk densities were determined to be 1.69 gms/cc in the sandy loam and 1.38 gms/cc in the silt loam. The X-ray diffraction patterns showed that the same clay minerals were present in the clay fraction of the sandy loam of this profile as were present in the other alluvial profile sampled.

TABLE I

PARTICLE SIZE DISTRIBUTION OF THE SOIL MATERIALS

	Fine Sandy Loam (%)	Salix Silt Loam (%)*	Sandy Loam (%)	Salix Silt Loam (%)/
Coarse sand	8.3	----	20.2	----
Med. sand	15.7	----	13.2	----
Fine sand	18.2	----	27.3	----
Very fine sand	16.6	----	11.4	----
Total sand	58.8	24.1	72.1	28.5
Total silt	32.2	56.0	19.9	51.6
Total clay	9.0	19.9	8.0	19.9

*this soil material was located beneath the fine sandy loam
/this soil material was located beneath the sandy loam

THE LABORATORY MODEL. A laboratory model was used to measure the velocity of flow from one soil layer to another and the hydraulic gradient at the plane of contact. Thus, the hydraulic conductivity was calculated from Darcy's equation. The front view of the laboratory model is shown in Figure 1 and the back view is shown in Figure 2. The front of the model was formed by a sheet of clear plastic which was cut into six rectangular sections so that a separate section formed the front of each of the six compartments. The back of the model was formed by a
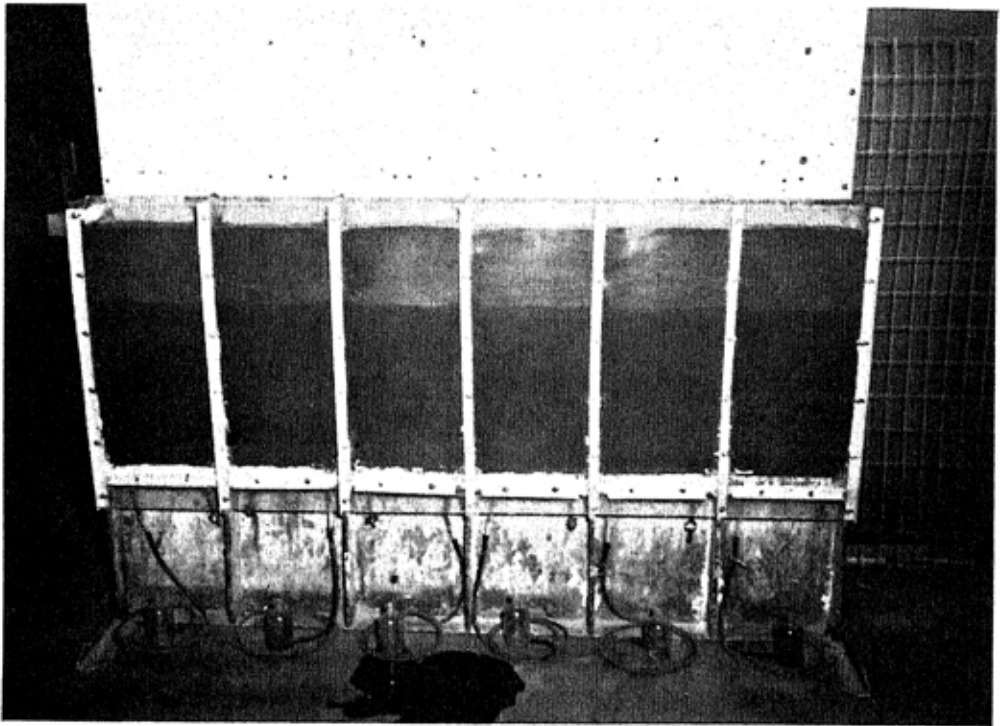
FIGURE 1. Front view of the Laboratory Model with sandy loam in the upper twenty cm (light layer) and Salix Silt Loam in the lower forty-five cm.
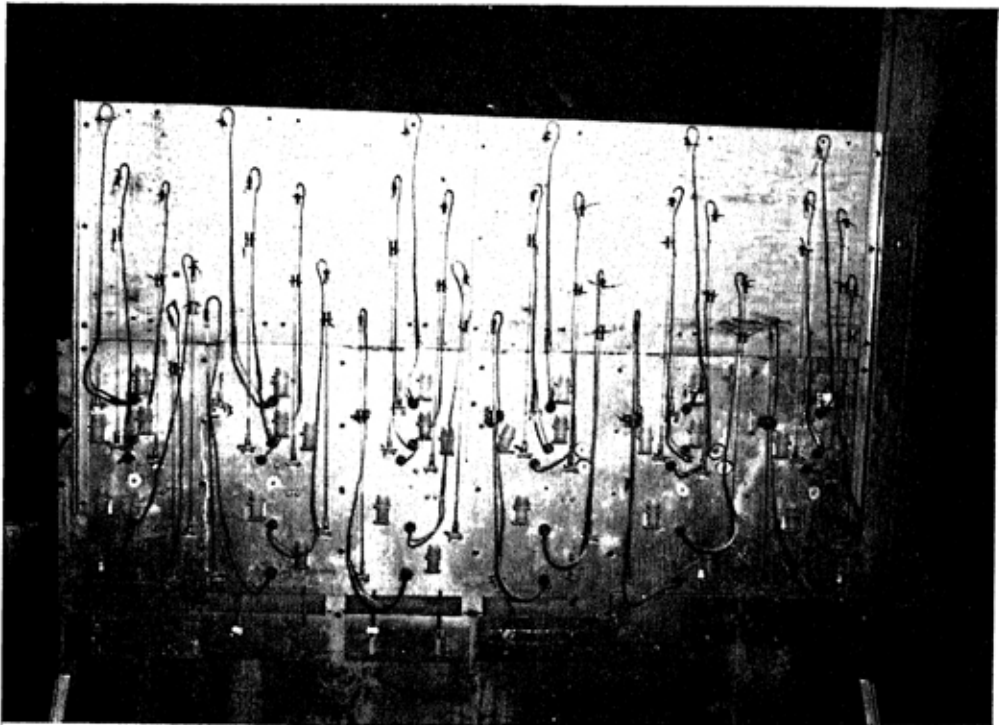

FIGURE 2. Back view of the Laboratory Model showing the Mercury Manometers with Tensiometers inserted and Evaporation Windows partially opened.

one-fourth inch sheet of aluminum through which five holes per compart-
ment were drilled to accept the porous cups of tensiometers. The ten-
siometer cups were located at distances of 8, 18, 22, 38 and 48 cm
from the top of the soil columns. Each tensiometer cup was connected
to a flexible plastic tube which was attached to a glass capillary tube that
had its lower end submerged in a mercury well. Near the bottom of each
compartment, a twenty-six by eight cm section was cut from the aluminum
and fitted with a sliding plate so that the area of soil exposed to evapora-
tion could be controlled. Each of the six compartments was 30.5 by 7.6
cm. in cross section and seventy cm in height.

The bottom of each compartment was designed to allow water to
be introduced into the soil column. It was formed of clear plastic which
was drilled and fitted with two plastic tubes, one of which was about three
feet long and was connected to a leveling bulb. The other plastic tube was
about six inches long and was closed with a pinch clamp. It's purpose was
to help remove entrapped air at the start of the saturation process. A
wire screen was placed on top of the clear plastic tubes so that the tube
openings were covered.

The model was enclosed in an insulated chamber so that the
temperature could be controlled. The temperature was maintained at
twenty-two degrees centigrade with a variation of one half degree. The
humidity in the chamber was not measured, but it was kept at a low value
by using a dehumidifier.

PROCEDURE. The plastic front of the model was marked with
horizontal lines in five cm intervals in order to obtain the desired com-
paction of the soil in each of the six compartments. The six compart-
ments were packed with soil in the same manner so that there were six
similar soil columns at the start of each test. Sufficient soil was weighed
separately to fill each five cm depth of each soil column at a given bulk
density and moisture content. The weighed soil was then poured into one
of the compartments and tamped to the proper line.

One soil material was packed in the lower forty-five cm of each
soil column and a different soil material in the upper twenty cm. When
the soil was packed in this manner the plane of contact between the two
soil materials was located between the two closest tensiometers so that
one was two cm above the plane of contact and the other was two cm
below.

After the soil was packed in the model, the saturation process was
begun. Water was introduced at the bottom of the soil columns from the
leveling bulbs. Water entering from the bottom of the column would not
saturate the coarse material when it was overlying the fine material with
the amount of head that could be obtained. In order to completely saturate
the column the upper coarse material was saturated from the surface by

adding water to one side of the column so that as little air as possible was entrapped.

The tensiometer cups were inserted into the soil soon after saturation by removing a core of soil with a cork borer and inserting a tensiometer into the intervening space. Daily readings of the mercury manometers were made as the suction in the soil increased due to the loss of moisture by gravity at first and then by the hydraulic gradient developed by the evaporation of moisture at the base of the column. Covering the tops of the soil columns prevented evaporation. The cover was composed of a damp cloth sandwiched between two pieces of thin flexible plastic. The damp cloth decreased the vapor pressure gradient between the nearly saturated soil air and the unsaturated surrounding air. Loss of moisture from the base of the columns was controlled by regulating the sliding plates so that the area of each soil column exposed corresponded inversely to its relative dryness as indicated by the tensiometers. Evaporation was controlled so that all columns would contain the same amount of water at any given time. The amount contained in the upper soil material at a given time was determined by removing that material from one of the columns. The upper soil material of each soil column was removed after a different length of time had elapsed since saturation. This made it possible to obtain six observations of the variation in moisture content with time which is a measure of the velocity of flow.

The other value of Darcy's law which is necessary in order to calculate the change in hydraulic conductivity over an interval of time is the hydraulic gradient i. Values for i were obtained at the plane of contact from the tensiometer readings and positions. The change in hydraulic head along the line of flow gives the hydraulic gradient. The hydraulic head in cm of water was obtained by converting the mercury manometer readings to cm of water by multiplying them by 12.6. This value is the density of mercury minus the density of the water which is partially balancing it on the other side of the loop of tubing connecting the tube filled with mercury to the tensiometers. Since the tensiometers were located at different vertical positions the manometer readings had to be corrected for the different amount of head of water above them. This correction was made by choosing the plane of contact as the datum level and adding the distance between the tensiometer cup and the datum level to those tensiometers located below the datum level and subtracting this value from the readings of those above. In this manner, the hydraulic gradient was obtained and Darcy's law was used as an evaluation of moisture transfer from one soil layer to another.

Tests were made using an aggregated upper soil material. The soil was aggregated by adding two percent Na-hydroxy poly-acrylonitrile

(Krilium) and stirring the soil as water was added until the average size of the aggregates was about three millimeters.

DATA AND DISCUSSION

MOISTURE MOVEMENT FROM SAND TO SILT LOAM. The first test was made on water movement from graded sand to Menfro silt loam. The summarized data are shown in Table II. As the moisture content approached a constant value, the hydraulic gradient at the plane of contact increased rapidly. This was because of the rapid loss of moisture from the sand. One reason for this was the small amount of moisture left in the sand after a short drainage time. The almost constant moisture content of the sand after the tenth day indicates that it has reached field capacity.

The hydraulic conductivity at the plane of contact remained at one or two cm per day for the first four days after saturation while the water held in the large pores in the sand was in contact with the smaller pores in the silt. After the large pores were emptied and water remained only at the points of contact between the sand grains, the hydraulic conductivity was practically zero. Under this condition, the plane of contact between the two soil materials could be characterized as having a small number of small pores in the sand in contact with a large number of small pores in the silt loam. Water movement was slow because of the insufficient supply of water at the plane of contact because of the discontinuous nature of the water films in the sand.

TABLE II
MEASURED VALUES OF HYDRAULIC GRADIENT AND MOISTURE CONTENT OF THE SAND AND CALCULATED VALUES OF HYDRAULIC CONDUCTIVITY OBTAINED WITH MOISTURE MOVEMENT FROM SAND TO SILT LOAM.

Days Since Saturation	Moisture % by Vol.	Hydraulic Gradient	Hydraulic Conductivity
1	14.93	−2.0 cm water/cm	28,600 cm/day*
5	3.17	−26.4 cm water/cm	219 cm/day*
10	2.64	−53.8 cm water/cm	3.90 cm/day*
19	2.20	−70.5 cm water/cm	1.40 cm/day*
26	2.16	−107.8 cm water/cm	0.11 cm/day*
33	2.11	−130.8 cm water/cm	0.09 cm/day*

*Each value should be multiplied times 10^{-4}

MOISTURE MOVEMENT FROM SILT LOAM TO SAND. The results of hydraulic tests with the direction of flow from silt loam to sand

are shown in Table III. These data show that the hydraulic gradients developed at the silt-sand contact plane were very small compared with those developed when moisture movement was in the reverse direction. The negative hydraulic head developed in the sand remained low and at about the same level as the suction in the silt loam.

The moisture content decrease in the silt loam was very small over the twenty-six days of the experiment with the change occurring as a decrease from forty-four to forty percent by volume. There was practically no change in the moisture content after the fourteenth day. Thus, the silt loam had reached a field capacity at about forty percent moisture. The moisture content of the silt loam at one third bar of suction from the pressure membrane apparatus was 26.6 percent by volume. Thus, the sand beneath the silt loam produced a perched water table in the silt loam.

In order for water to move in the unsaturated state from the small pores in the silt loam to the large pores in the sand, the suction in the sand had to be greater. Thus, the moisture content of the silt loam was determined by the suction of the sand beneath it. The maximum suction developed in the sand in the model was sixty cm of water. Sixty cm of water suction on the silt loam brought it to a moisture content of forty-one percent by volume as determined in the pressure membrane apparatus. This value agrees very well with the final moisture content of the silt loam as shown in Table III.

TABLE III
MEASURED VALUES OF HYDRAULIC GRADIENT AND MOISTURE CONTENT IN THE SILT LOAM AND CALCULATED VALUES OF HYDRAULIC CONDUCTIVITY OBTAINED WITH MOISTURE MOVEMENT FROM SILT LOAM TO SAND

Days Since Saturation	Moisture % by Vol.	Hydraulic Gradient	Hydraulic Conductivity
1	43.79	-0.25 cm water/cm	0.9520 cm/day
7	41.72	≠1.25 cm water/cm	0.0671 cm/day
14	40.85	≠1.20 cm water/cm	0.0118 cm/day
19	40.01	≠1.0 ccm water/cm	0.0087 cm/day
22	40.35	-1.0 cm water/cm	0.0114 cm/day
26	40.23	-1.0 cm water/cm	0.0108 cm/day

MOISTURE MOVEMENT FROM FINE SANDY LOAM TO SALIX SILT LOAM. The results of the hydraulic tests with the flow direction from fine sandy loam to Salix silt loam are shown in Table IV. The bulk density of the sandy loam layer was 1.63 gms/cc and that of the silt loam was 1.37 gms/cc. The data show that the hydraulic gradients

remained near unity throughout the experiment. As moisture was lost from the silt loam at the bottom of the soil columns, the negative hydraulic head increased in the silt loam. The influence of the drying silt loam was exerted on the fine sandy loam across the boundary between the two soil materials, indicating that the break in texture did not greatly affect water movement. Further indications that water movement is relatively unrestricted is furnished by the continuous decrease in moisture content in the fine sandy loam and the nearly constant value of the hydraulic conductivity. The reasons for the good conductivity across the boundary are attributed to the higher degree of compaction and the specific range in particle size of the fine sandy loam layer.

TABLE IV

MEASURED VALUES OF HYDRAULIC GRADIENT AND MOISTURE CONTENT OF THE FINE SANDY LOAM AND CALCULATED VALUES OF HYDRAULIC CONDUCTIVITY OBTAINED WITH MOISTURE MOVEMENT FROM FINE SANDY LOAM TO SALIX SILT LOAM

Days Since Saturation	Moisture % by Vol.	Hydraulic Gradient	Hydraulic Conductivity
1	34.15	-1.25 cm water/cm	1.89 cm/day
6	24.89	-0.50 cm water/cm	0.37 cm/day
19	19.17	-2.30 cm water/cm	0.09 cm/day
27	16.76	-0.25 cm water/cm	0.038 cm/day
33	17.56	-2.35 cm water/cm	0.043 cm/day
42	14.90	-2.00 cm water/cm	0.029 cm/day

MOISTURE MOVEMENT FROM AGGREGATED FINE SANDY LOAM TO SILT LOAM. Tests were made to determine the effect of an aggregated fine sandy loam surface on water movement into the silt loam. After aggregation, the fine sandy loam layer was placed in the model above the silt loam which was compacted to a bulk density of 1.37 gms/cc. The results of the tests on water movement from the aggregated layer to the silt loam are shown in Table V. The table shows that the hydraulic gradient from the aggregated fine sandy loam to the silt loam was not much different from the hydraulic gradient of the unaggregated material, for it remained near unity over the range of suction developed.

The similar hydraulic conductivity values indicate that aggregation of the fine sandy loam had very little effect on moisture movement between the two soil layers. This similarity may have been caused by the particle size distribution of the fine sandy loam, for the individual aggregates must have compacted during aggregation to a bulk density comparable with that measured in the field, although the measured bulk density

of the aggregated layer in the model was 1.31 gms/cc. If the individual aggregates were compact, then the water would again be moving from a compacted fine sandy loam to silt loam as soon as the large pores between the aggregates were emptied so that the flow of moisture was through the aggregates rather than around them.

TABLE V

MEASURED VALUES OF HYDRAULIC GRADIENT AND MOISTURE CONTENT OF THE FINE SANDY LOAM AND CALCULATED VALUES OF HYDRAULIC CONDUCTIVITY OBTAINED WITH MOISTURE MOVEMENT FROM AGGREGATED FINE SANDY LOAM TO SALIX SILT LOAM

Days Since Saturation	Moisture % by Vol.	Hydraulic Gradient	Hydraulic Conductivity
1	30.54	-0.50 cm water/cm	3.52 cm/day
4	23.44	-4.00 cm water/cm	0.37 cm/day
11	21.68	-0.43 cm water/cm	0.056 cm/day
19	19.73	-0.93 cm water/cm	0.031 cm/day
27	18.98	-2.90 cm water/cm	0.023 cm/day
33	18.08	-1.38 cm water/cm	0.011 cm/day

MOISTURE MOVEMENT FROM SANDY LOAM TO SILT LOAM. The results of the hydraulic tests made on the third pair of soil materials are shown in Table VI. The sandy loam layer was placed loose in the model and the silt loam layer was compacted to 1.38 gms/cc. Bulk density measurements after saturation of the sandy loam layer showed that it had compacted to 1.61 gms/cc making this test comparable with that of the compacted fine sandy loam over silt loam. The data show this similarity. The fact that the loose sandy loam became compacted when saturated is an indication that because of the particular arrangement of particle sizes in this soil material high bulk density values and small pore sizes are natural to it. This means that the "traffic pans" common to sandy alluvial soils may be the result of certain properties of the soil materials rather than the result of their inability to support heavy equipment. However, as has been shown by this study, traffic pans in a coarse material which is in contact with a finer material located beneath it may contribute to water movement. In this instance, the undesirable features of the traffic pan are confined to the restrictions placed upon root penetration by its presence.

TABLE VI

MEASURED VALUES OF HYDRAULIC GRADIENT AND MOISTURE CONTENT OF THE SANDY LOAM AND CALCULATED VALUES OF HYDRAULIC CONDUCTIVITY OBTAINED WITH MOISTURE MOVEMENT FROM SANDY LOAM TO SALIX SILT LOAM

Days	Moisture % by Vol.	Hydraulic Gradient	Hydraulic Conductivity
1	32.85	−0.25 cm water/cm	2.71 cm/day
6	21.83	−0.50 cm water/cm	0.380 cm/day
12	17.99	−2.80 cm water/cm	0.113 cm/day
19	16.07	≁1.00 cm water/cm	0.050 cm/day
26	14.91	−2.35 cm water/cm	0.030 cm/day
31	14.35	−1.00 cm water/cm	0.023 cm/day

CONCLUSIONS

The general conclusions of this study are:

1. Water movement from larger pores to smaller pores is practically unrestricted at the contact zone if the volume of both is about the same and the size difference is not extremely great;

2. Water movement from a system of small pores to one of larger pores is very slow in the unsaturated state.

The larger pores are emptied soon after suction is applied to the saturated soil. In order for water to move out of the small pore system it must enter the large pores at the same suction. As suction increases, the films of water around the large pore spaces on the solid surfaces decrease to thin films. Therefore, as the suction increases in the small pore system the volume of water filled pore space in the large pore system decreases rapidly and moisture flow decreases at a corresponding rate.

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