Soil Layering and Compaction Effects on Unsaturated Moisture Movement[1]

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ABSTRACT

Measurements of the velocity of flow and hydraulic gradients were obtained in the suction range of 0 to 700 cm. of water across the plane of contact for three different soil textural pairs, two of which were sampled from naturally occurring textural breaks in alluvial soil profiles. The hydraulic conductivity values across the textural breaks indicated that the soil properties were favorable for moisture transfer from large pores to smaller pores, but that a barrier existed for water movement from smaller pores to large pores. The barrier developed as the suction increased in a coarse layer in contact with finer material. With water removal from the larger pores at moderately low suctions, flow from the fine soil layer into the coarse material was reduced. 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.

THERE ARE FEW SOILS in the field which have uniform texture and structure throughout the profile. 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 were the basis of this study.

Diebold (3) reported that more than 40% silt in a soil hinders water movement and suggested that it acts as a clogging material in medium-textured soils. He also showed that the degree of compaction influences water movement.

Some of the effects of layering of soils were studied by Alway and McDole (1). They used six different layers of soil in a cylinder to show 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 held more water than when the sand layer was absent or located above them. Day and Luthin (2) found that soil moisture near the contact zone of a layered soil was held under suction even though a continuous head of water was maintained on top of the column.

Scott and Corey (4) derived an equation which describes the pressure distribution during steady flow in a porous material. Theoretical values from the equation agree well with their experimental data, which show decreased pressure in a sand layer overlying a fine-textured sand layer.

This paper reports on investigations of the water-transporting properties existing in soil columns composed of layers of soil differing in texture, structure, or compaction. These properties were studied by using the hydraulic conductivity values of Darcy's law calculated for a 1-cm. interval including the plane of contact of the different soil materials. The hydraulic conductivity was calculated from measurements of the hydraulic gradient and velocity of flow from the top soil layer to the lower. The hydraulic gradient was measured for a 4-cm. interval from which the curve was extrapolated to obtain the hydraulic gradient of the 1-cm. interval which included the junction between the two soils.

MATERIALS AND METHODS

The Soils

Three different pairs of soil materials were used. The first pair was a graded sand in contact with a loessial-derived silt loam. The sand used had a diameter range from 250 to 300μ. 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% sand, 55.5% coarse silt, 16.5% fine silt, and 13.0% 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 10 inches of the profile was a fine sandy loam with an abrupt break to a silt loam at 10 inches. The particle size distribution as determined by the hydrometer and wet-sieve methods is shown in table 1. Bulk density samples taken with the Uhland sampler, were determined to contain 1.63 g. per cc. in the fine sandy loam and 1.37 g. per cc. in the silt loam. X-ray diffraction patterns indicated that the clay fraction in both the surface fine sandy loam and the underlying silt loam were composed of a mixture of montmorillonite, kaolinite, and illite clay minerals.

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 8½ 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 were made on the Salix silt loam with a fine sandy loam overwash. The particle size distribution is shown in table 1. The bulk densities were determined to be 1.69 g. per cc. in the sandy loam and 1.38 g. per cc. in the silt loam. The X-ray diffraction patterns showed that the same mixture of clay minerals was present in the clay fraction of the sandy loam and silt loam of this profile as was present in the other alluvial profile sampled.

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 junction region. Thus, the hydraulic conductivity was calculated from Darcy's equation, which is $V = Ki$, where V is the velocity of flow, K is the hydraulic conductivity, and i is the hydraulic gradient. The front view of the laboratory model is shown in figure 1. The back of the model was formed by a ¼-inch sheet of aluminum through which 5 holes per compartment were drilled to accept the porous cups of tensiometers. The tensiometer 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 mercury well by a glass capillary tube. Near the bottom of each compartment, a 26-cm. by 8-cm. section was cut from the aluminum and fitted with a sliding plate so that the area of soil exposed to evaporation could be controlled.

Table 1—Particle size distribution of the soil materials.

	Fine sandy loam (%)	Salix silt loam (%)*	Sandy loam (%)	Salix silt loam (%)†
Coarse sand	8.3	-	20.2	-
Medium 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

* Beneath the fine sandy loam. † Beneath the sandy loam.

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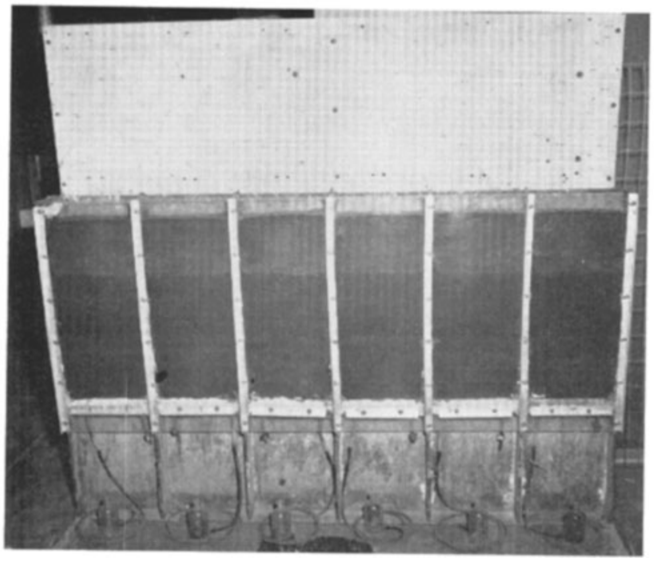

Figure 1—Front view of the laboratory model with sandy loam in the upper 20 cm. (light layer) and Salix silt loam in the lower 45 cm.

The model was enclosed in an insulated chamber so that the temperature could be controlled. The temperature was maintained at 22°C. with a variation of ½°C. 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 5-cm. intervals in order to obtain the desired compaction of the soil in each of the six compartments. The six compartments 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 5-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 45-cm. of each soil column and a different one in the upper 20 cm. With the soil packed in this manner the plane of contact between the two soil materials was located between the two closest tensiometers so that one was 2 cm. above the plane of contact and the other was 2 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. With the amount of head that could be obtained, water entering from the bottom of the column would not saturate the course material when it was overlying the fine material. 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. Evaporation from the tops of the soil columns was prevented by covering them. 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. The loss of moisture was thus regulated by the plates 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 gave a measure of the velocity of flow.

Table 2—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 volume	Hydraulic gradient	Hydraulic conductivity
1	14.93	- 2.0 cm. water/cm.	28,600 cm./day*
5	3.17	- 26.3 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 by 10^{-4}.

Table 3—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 volume	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 cm. water/cm.	0.0087 cm./day
22	40.35	-1.0 cm. water/cm.	0.00114 cm./day
26	40.23	-1.0 cm. water/cm.	0.00108 cm./day

Tests were made using an aggregated upper soil material. The soil was aggregated by adding 2% Na-hydroxy polyacrylonitrile (Krilium) and stirring the soil as water was added until the average size of the aggregates was about 3 mm.

RESULTS 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 2. As the moisture content approached a constant value the hydraulic gradient at the plane of contact increased rapidly. This increase was due to the rapid loss of moisture from the silt loam without a corresponding loss of moisture from the sand. One reason for this difference 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 10th day indicates that it had reached field capacity.

The hydraulic conductivity at the plane of contact remained at 1 or 2 cm. per day for the first 4 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 the water in the sand became concentrated at the contact points 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 due to the discontinuous nature of the water films in the sand.

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 3. 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 26 days of the experiment with the change occurring as a decrease from 44 to 40% by

Table 4—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 volume	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

Table 5—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 volume	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	-9.43 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	-1.35 cm. water/cm.	0.011 cm./day

Table 6—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 since saturation	Moisture % by volume	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

volume. There was practically no change in the moisture content after the 14th day. Thus, the silt loam had reached a field capacity at about 40% moisture. The moisture content of the silt loam at ⅓ bar of suction from the pressure membrane apparatus was 26.6% by volume. Thus, the sand beneath the silt loam restricted the drainage from 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 at least as great as that of the silt loam. 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 60 cm. of water. Sixty centimeters of water suction on the silt loam brought it to a moisture content of 41% 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 3.

The hydraulic gradients reported are an average of the remaining unsampled soil columns. The positive values seem erratic at first. However, they were measured in millimeters of mercury and converted to centimeters of water. The readings were measured to the nearest millimeter. One millimeter of mercury is equal to 1.26 cm. of water. Therefore, when positive values occurred, unit negative hydraulic gradient was assumed for calculating the hydraulic conductivity.

Moisture Movement from Fine Sandy Loam to Salix Silt Loam

The results of the hydraulic test with the flow direction from fine sandy loam to Salix Silt loam are shown in table 4. The bulk density of the sandy loam layer was 1.63 g. per cc. and that of the silt loam was 1.37 g. per 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 was 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 good conductivity of water across the boundary are attributed to the higher degree of compaction and the specific range in particle size of the fine sandy loam layer.

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 g. per cc. The results of the tests on water movement from the aggregated layer to the silt loam are shown in table 5. The table shows that the hydraulic gradient from the aggregated fine sandy loam to the silt loam was not very different from the hydraulic gradient of the unaggregated material in that it remained near unity over the range of suction developed.

The similar hydraulic conductivity values indicate that aggregation of the fine sand loam had very little effect on moisture movement between the two soil layers. This similarity may have been due to the particle size distribution of the fine sandy loam in that 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 g. per 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.

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 6. The silt loam layer was placed in the model and compacted to 1.38 g. per cc. while the sandy loam layer was allowed to remain loose in the model. Bulk density measurements after saturation of the sandy loam layer showed that it had compacted to 1.61 g. per cc. making this test comparable with that of the compact fine sandy loam over silt loam. The data bear out this similarity. The fact that the loose sandy loam became compact 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 favorably to water movement. In this case the undesirable features of the traffic pan are confined to the restrictions placed upon root penetration by its presence.

CONCLUSIONS

The general conclusions of this study can be stated in two points:

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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