SOIL-WATER RELATIONSHIPS IN STRATIFIED SANDS

Thesis for the Degree of Ph. D.
MICHIGAN STATE UNIVERSITY

Jamal Sharif Dougrameji

1965

This is to certify that the

thesis entitled

"Soil-moisture relationships in stratified sands"

presented by

Jamal S. Dougrameji

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Soil Science

A. E. Erickson
Major professor

Date July 30, 1965

O-169

ABSTRACT

SOIL-WATER RELATIONSHIPS IN
STRATIFIED SANDS

by Jamal S. Dougrameji

The purpose of this investigation was to study the effect of stratification in sand columns on moisture movement and distribution. Strata of various particle sizes and thicknesses were studied using soil moisture content and moisture tension measurements under static conditions and conditions where water was applied from the bottom or with various rates of water application from the top. Water manometers and a strain gauge pressure transducer were used to follow moisture tension changes in sand columns.

The results of this investigation showed that moisture discontinuities do exist in sand when a coarse layer underlays a fine layer, as well as the reverse. Furthermore, it was shown that discontinuities are a function of the difference between the particle size of the strata and that of the bulk of the column.

Although the tension required to drain a sand separate depends on its particle size, in stratified sands the

size of the particles and distribution of the coarse strata govern the drainage of the entire profile.

The thickness of the strata does not affect the magnitude of discontinuity once the minimum thickness to cause the discontinuity is reached. This minimum thickness in an ideal, well-differentiated stratum is probably one particle thick.

In the case where water is infiltrating the column, the magnitude of discontinuities is a function of water application rate.

A mechanism based on the phenomena of surface tension and capillary rise is suggested to describe the movement of moisture in the stratified sand columns. When a coarse sand layer is underlying a fine sand layer, the wetting front advances downward in the upper fine layer until it contacts the coarse layer. At the interface of the two layers a change in particle, as well as pore size occurs. Because the coarse layer is incapable of conducting the water at a high tension, which exists at the interface, the wetting front advance stops. In order for the wetting front to continue downward, the moisture tension above the coarse stratum must decrease by water accumulation until the tension is low enough to allow the conduction of water around the particles and through a few wet pores in the coarse strata. Once the water reaches the bottom of the coarse layer, the water moves into the fine layer below. The higher attraction of the fine sand for water causes the wetting front to continue to advance.

The results of this investigation are applicable in soil water conservation practices in sand and other texturally stratified soils. Formation of perched water table or an increase in water holding capacity of the soil above the coarse stratum may increase the available moisture for plant growth. The frequency of irrigation in these soils may be decreased. Furthermore, the rate of evaporation may be decreased. The presence of coarse strata may determine the depth of the tile drains. Also in some cases textural stratification could create serious aeration problems and slow the recharge of aquafiers.

SOIL-WATER RELATIONSHIPS IN STRATIFIED SANDS

By

Jamal Sharif Dougrameji

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

1965

ACKNOWLEDGMENTS

The author wishes to express his sincere apprecation to Dr. A. E. Erickson for his guidance and suggestions during the course of this study. His interest and encouragement of fundamental research has been of great value in the completion of this study.

The author would also like to thank the members of his guidance committee for their helpful suggestions concerning the authors program.

The financial assistance provided by the Republic of Iraq and by the Michigan State University is gratefully acknowledged.

Special thanks goes to my wife, Kawkab, for her encouragement and understanding.

TABLE OF CONTENTS

LIST OF TABLES

Table		Page

Table		Page

LIST OF FIGURES

Figure		Page

Figure | Page

Figure		Page

I. INTRODUCTION

The importance of adequate water supply for maximum plant growth has long been recognized. The pattern of water movement in saturated and unsaturated conditions is not only important in the field of soil science, but also important in the fields of hydrology, engineering and plant physiology.

Soil physicists have contributed valuable knowledge to the understanding of moisture movement into and within homogeneous soils. However, less attention has been given to the movement of water into stratified soils.

Soils are composed of horizons developed by the processes of soil formation. These horizons differ in texture due to processes of soil formation, but many are texturally stratified as a result of modes of deposition. Soil material that has been deposited or worked by water is frequently stratified. This is an especially important phenomenon in glaciated regions such as occur in Michigan.

Sand soils in general have a low water holding capacity and high rate of water infiltration, but some sand soils differ greatly in these physical properties. Field observations indicate that textural stratification of the sand in some of these soils is the cause of their anomalous behavior.

These stratified sands have often increased water holding capacities, lowered water transmission rates and may have perched water tables. They may present problems in drainage and irrigation.

Although there have been some studies, these were restricted mostly to stratified conditions in structural soils, and the available data are not sufficient to evaluate the effect of various single grained textural strata on moisture movement and distribution.

The purpose of this study is: (1) to measure the effects of stratification in sands on water movement and moisture distribution in these soils and (2) to determine the particle size difference necessary to produce soil moisture discontinuities in these materials.

This study is based on a laboratory investigation in which moisture content, moisture tension and moisture movement with time could be observed in stratified sand columns.

II. LITERATURE REVIEW

A. Capillary rise in uniform and stratified soils

The soil is a heterogeneous system in nature and there are very few soils in the field with uniform texture or structure. One of the properties of stratified soils is textural variation of the strata. The texture, or size distribution and arrangement of particles result in variation in pore size distribution. Since the soil water must move through the pore spaces of the soil, the changes in the texture of the various layers affect the movement and distribution of the water. The rate of water movement through stratified soil depends upon whether the water is moving upward or downward.

The investigation of the processes involved in the movement of water into and within the soil is not new.

Fireman (13) reported that the first experimental studies which can be regarded as a theoretical basis for the movement of fluids through porous media were performed by Hagen in 1839 and Poiseuille in 1846. They studied the flow of fluids through capillary tubes and concluded that the rate of flow was proportional to the hydraulic gradient.

Schumacher in 1864, as cited by Baver (3), introduced the concept of capillary and non-capillary porosity and showed that the amount of water the soil can hold is related to the size of the soil particles, which in turn determines the size and number of the capillary pores.

Wollney in 1885 (3) studied various factors which affect the capillary rise of water in soils. He concluded that soil capillary pore spaces from 0.05 to 0.1 millimeters in diameter conducted water the most rapidly, and that capillary rise reached a minimum limit with quartz particles larger than 2 millimeters in diameter. The results obtained by Wollny showed that coarse textured soils have a rapid initial rate of capillary rise, but that fine textured soils have the highest rise.

Loughridge (24) in 1894 obtained similar results. He concluded that the rate of capillary rise of water in soils is controlled by the proportion of coarse material. The height of capillary rise is also dependent upon the amount of fine silt and clay. He found that in sand soils the capillary rise is less than 18 inches.

Harris and Turpin (17) studied, in detail, the movement and distribution of moisture in the soil. They observed very little rise of moisture from clay into loam but slow and continuous capillary rise from loan into clay. Furthermore, they found high and rapid rise from sand into loam and quite rapid from loam into sand. They concluded that with the soil increasing in fineness from the source of water, there was considerable and prolonged rise of water, while with the reverse order of fineness, the rise was very rapid for the first few weeks, but a decided falling off occurred when the coarser layers were reached.

McLaughlin (27), in a study of capillary rise, observed that the rate of water rise in the coarser soils was more rapid for the first few hours, then it slowed down quicker than with heavy soils. The height of the capillary rise in coarse textured soils was less in a long period of time. In further studies (28) he observed that the moisture was not distributed at a uniformly decreasing content with height above the water table. When the downward movement of moisture was restricted by an impervious stratum, the distribution, in time, of moisture above this stratum, was similar to the distribution of moisture in a vertical soil column extending upward from this stratum, and with a water talbe at the stratum.

Dougrameji (7) found that the height of capillary rise of water increased with a decrease in the particle size of the separates. For all separates there was an increase in the capillary rise of water with an increase in time. The capillary rise occurred mainly during the first 48 hr. The most significant difference in the total rise of water was with particle sizes of less than 0.25-0.1 mm diameter in which there was a greater increase in capillary rise compared to the coarser fractions.

Mamanina (26) in a study of the effect of restrictive interlayers on the height of capillary rise of water in heavy loam soils found that a 2 cm layer of coarse 2.5-1 mm diameter particles completely restricted the capillary rise of water. Gravel of 3-7 mm diameter was less effective and a thicker layer was needed due to intermixing of the layers. Medium sand of 1-0.5 mm diameter was without effect.

Felitsiant (10,11) studied, in detail, the capillary rise of water in uniform and stratified soils using clay, sand and loessial clay loam in a tube 2.7 cm in diameter and 100 cm long. The arrangement of the layers in the tube were (1) uniform texture, (2) stratified texture, coarser from bottom to top, (3) stratified texture, finer from bottom to top and (4) stratified texture with mixed distribution of the layers. He showed the dependence of capillary rise on the texture of the layers, their thickness, and their distribution in soil. He observed that when a coarse layer was underlain by a fine textured layer, there was an increase in rate of capillary rise of water in the fine layer as compared with uniform fine textured soil, and a decrease in the rate of capillary rise occurred in the upper coarse layer. A greater reduction in the rate of capillary rise occurred where the thickness of the bottom layer was increased. On the other hand, when fine textured soil was underlain by a coarse textured soil, the rate of capillary movement in the lower layers decreased while in the upper layer it increased until a certain maximum thickness of the lower layers was reached.

Felitsiant (11) suggested that the height of capillary rise is determined by the relationship of stimulating and impeding factors. Meniscus forces pertain to the former, the weight of water in the capillaries and friction pertain to the latter. Capillary movement continues until the latter forces balance the former, and once equilibrium between these two forces occurs, capillary movement ceases and the moisture in the soil stays at the level of the peak height of capillary rise.

Staprens (43) in a theoretical analysis of the movement of capillary-moisture in sandy soils, showed that the capillary bound moisture above a water barrier was held either as perched or suspended capillary water. The perched water was held either as capillary water in horizons lying above the water table or those lying above the absolute or relative water barrier. On the other hand capillary-suspended water was held in a soil by a force field which counteracted the gravitational force. Furthermore, he reported that the thickness of the suspended capillary water was equal to the difference between the capillary rises of the upper and lower layers.

B. Soil moisture retention in stratified soils.

Effects of stratification on retention of water were studied as early as 1917 when Alway and McDole (1) 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 when situated above a layer of coarse sand than when the sand layer was absent or located above them.

Lebedeff (22) in a series of experiments showed that in a soil where a large grained sand was overlaid by a fine grained sand, more water was retained in the fine grained sand than if it was underlaid by material of the same size. If the coarse grained sand was underlaid by a fine grained sand then no increase in moisture was observed in the coarse grained layer.

Bol'shakov (5) in his work on moisture regime in two layered Chernozem soils under natural conditions, obtained similar results when he found that more moisture was held in the layer of fine clay loam above a layer of a coarse silty clay loam.

Nelson and Baver (37) placed 40-60 mesh sand on a pressure plate, with 150-270 mesh sand above. The system was saturated and the desorption characteristics determined. They found that the upper fine layer remained nearly saturated after the coarse layer had drained.

Similar results were obtained by Miller and Bunger (31,32) in evaluating the effects of various arrangements of coarse strata in the profile, on the moisture retention characteristics of the soil above the strata. They compared layered and uniform soils in artificial profiles constructed by digging pits and refilling them with layers of either sand or gravel and layers of uniform sandy loam, or with uniform loam only. The 8 by 10 feet pits were 5 feet deep. They irrigated the profiles and covered them with plastic and straw to prevent evaporation. The moisture status of the soil was observed for 2 months following the irrigation. The moisture retention characteristics of the profiles were estimated from laboratory measurements on unsaturated conductivities of the sand and gravel, and from moisture characteristic curves of the soils.

The moisture retained by soil underlain by sand or gravel was much greater than in similar depths of a uniform soil. The moisture content of the soil above a coarse layer increased as the layer was approached. The moisture content of the soil underlain by sand or gravel changed very little after the first few days following irrigation, whereas in the uniform soil, moisture moved downward throughout the observation period.

C. Moisture movement in uniform and stratified soils.

Nelson and Baver (37) studied the relationship of pore size distribution to the water movement. In this study, seven quartz sand separates and aggregate separates of several soils were used. The moisture-tension curves were determined for each of the separates and for samples containing different layers of sand. Also percolation rates were determined.

The experimental results of Nelson and Baver showed that as the average size of the particle decreased, the percolation rates decreased and the tension required to drain the pores in the system increased. It was necessary to bring each separate to a certain tension before any appreciable amount of water was removed from the system. When a high enough tension was reached to drain the pores of the separate, water came out very rapidly.

Luthin (25) in his investigation on the effect of layering on porosity and permeability under saturated conditions, concluded that no change in permeability resulted and a condition of reduced permeability does not exist at the interface of the layers.

Colman and Bodman (4,6) studied the water infiltration process under flooded conditions in laboratory packed columns of texturally uniform, air dry and moist Yolo sandy loam and silt loam soils. Layered columns of the two soils were also used and infiltration was studied with the columns initially dry.

Cumulative water entry and wetting front penetration data in relation to time in uniform soils showed linear relationships in both dry and moist conditions. In both soils the data representing water entry for the dry and moist columns were parallel, and showed that, at corresponding times, less water had entered the moist columns than the dry ones. The water penetration data were also similar but water penetration was more rapid in moist soils than in dry soils.

In layered soils where a sandy loam soil was overlaying silt loam and vice versa, the data showed that the less permeable layer limited water entry into the soil regardless of whether it lay above or below the more permeable soil. The rate of infiltration decreased with time for both layering combinations, but when silt loam overlay the sandy loam, the rate of decrease became less after the wetted front passed from the silt loam into a sandy loam.

Engleman and Jamison (9) investigated unsaturated movement of water as affected by soil layering and compaction in laboratory. They studied moisture movement from sand to silt loam, silt loam to sand, fine sandy loam to Salix silt loam, aggregated fine sandy loam to silt loam and from sandy loam to silt loam. After the soil was packed in the model, the saturation process was begun. Water was introduced at the bottom of the soil columns. 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. Daily readings of the tensiometers were made as the draining process started. The draining of moisture from the bottom was regulated so that all the columns would contain the same amount of water at any given time. The upper soil material of each soil column was removed, after a different length of time had elapsed since saturation, for moisture determination.

The result of the experiments showed that water movement from larger pores to smaller pores was unrestricted at the contact zone if the volume of both was about the same and the size difference was not extremely great. Water movement from a system of small pores to one of larger pores was very slow in the unsaturated state. The larger pores were emptied soon after tension was applied to the saturated soil. The soil, when underlain by sand, drained to a moisture content of about 40% by volume, compared to 1/3 atmosphere value of 27% by volume. The compaction of the different soil layers determined the degree of the restriction to water movement.

Scott and Corey (41) derived an equation which describes the pressure distribution during steady flow in porous material. Experiments were conducted using a hydrocarbon liquid and long columns of sand as porous media. Downward flow was measured through a sand and through a sand overlying another sand slightly finer in texture. All tests were on the drainage cycle.

The results of these experiments demonstrate that when steady flow was downward through a long column of unsaturated sand, the effective permeability tends to reach the same value in each stratum, provided the strata are sufficiently thick. At the bottom of a coarse-textured stratum, however, a region of very low saturation and permeability developed. They concluded that the zone of low effective permeability at the bottom of coarse-textured strata accounted for the low suctions in and above such strata for long periods following rains or irrigation.

Hanks and Bowers (16) devised and programmed a numerical solution of the moisture flow equation. Cumulative infiltration of the layered soils, a loam over silt loam and vice versa, was compared with uniform soils. The coarse over fine layered soil had the same cumulative infiltration curve as the coarse soil initially. Once the wet front reached the boundary, the curves separated, with the cumulative infiltration decreasing for the coarse over fine layered soil. A comparison of the uniform fine soil with the fine over coarse, showed very little to distinguish between the two conditions. Also, a comparison of infiltration rates for the same conditions gave similar results.

They concluded that, for the layered soils, the infiltration was governed by the least permeable soil layer once the wetting front reached this layer. The experimental results of Colman and Bodman agree with the results computed herein.

Miller and Gardner (33) studied infiltration rates into stratified soil. Infiltration rates and the position of the wetting front as functions of time were obtained for uniformly packed tubes of treated silt loam soil. Materials differing in particle size characteristics from the standard soil were used to form the strata in the soil columns.

They reported that the effects of strata within the soil profile were related to the pore size distribution differences between the layering materials and the surrounding soil. The infiltration rate was temporarily delayed after the wetting front reached the layers. The length of the delay increased when the pore size in the layer was increased.

Lebedeff (22) carried out an experiment where he added water continuously from the top to tubes of sand separates varied from 10 to 100 centimeters in height. The water addition was stopped after three hours. From one series of tubes samples were taken and moisture content was determined directly after water addition was stopped. The second series of tubes were left to drain until they reached equilibrium and then moisture content was determined.

The experiment showed that at the moment of infiltration the moisture content of the sand in all tubes was almost the same. But the distribution of moisture was varied at various heights of the tubes when the tubes were drained and reached equilibrium. The change in moisture distribution started with the tube of 30 cm high where the moisture content was decreased by almost 50% at 30 cm height. With column of 100 cm height, the moisture content distribution after 3½ days was determined. It was found that a layer with a constant moisture content was formed beginning with a height of 40 cm. Lebedeff called this moisture molecular moisture holding capacity. He concluded that an increase of the sand columns to 2, 3 and 4 m does not change the phenomenon observed in this column, and the moist layer located at the bottom of the tube remains unchanged.

Youngs (48) studied moisture content changes in a porous material during low rates of water infiltration. Using 0.04 to 0.125 millimeter slate dust with two rates of application, Youngs subjected his experimental results to a qualitative theoretical analysis. He showed that during infiltration at low rates into dry porous materials, which were wetted by drops of water, the porous material became locally saturated and then tended to drain until the next drop of water was added on the surface. However, very little drainage could occur in the early stages from such a small depth of water. Further drops of water incident on the surface wetted the porous material to a greater depth. When the depth of wetting became sufficiently great, the potential distribution down the profile was such as to permit the drainage of water from the near-saturated material close to the surface. At this stage, the material near the surface was draining while that near the moisture front was wetting. The initial zone of high moisture content near the surface gradually disappeared to form a moisture profile of fairly uniform moisture content behind the moisture front.

In a theoretical analysis of a series of studies on the effect of rate of application of water in relation to soil water, Rubin (39) found that the moisture contents of soil profiles during water infiltration might be considerably influenced by the rate of application. He showed that a continuous water application resulted in ponding if the rate of application exceeded the saturated hydraulic conductivity of the soil. When rate of application was equal or less than saturated hydraulic conductivity soil moisture contents at increasing depths tended to approach a constant level as infiltration proceeded. At this point the soil hydraulic conductivity was equal to the rate of water application.

In order to prove the validity of these theories, Rubin and co-workers (40) carried out an experiment using two different uniform textured columns with different rates of water application. They obtained moisture content data throughout the column. This data indicated that the moisture contents in the column increased with increasing rates of water application. The moisture content was the highest with high rates of application. The moisture contents at increasing soil depths approached a constant level with time. The lower rates of application produced a lower level of moisture content.

Willis (46) obtained data on evaporation from layered soil. These data indicated that the presence of a coarse textured layer under a fine surface layer made little difference in the evaporation of water until the water table was lowered a distance below the boundary line between the layers. On the other hand, when a coarse surface layer was underlain by a finer layer, there was a decrease in rate of evaporation dependent on the thickness of the coarse layer and the depth of the water table.

D. Soil moisture tension measurements.

Measurements of soil moisture tension have received major attention from those concerned with water relations of soils and plants as well as those concerned with physical and engineering properties of soil.

Richards (38) had reviewed the contributions of various investigators concerning the use and development of tensiometers. The various types of tensiometers all use the same principle. A water-saturated porous cup is maintained in contact with the soil and is connected by a sealed water column to a vacuum measuring gauge, water manometer or mercury manometer. The soil moisture tension at equilibrium can be read directly.

The tensiometer is a major tool in studying many aspects of soil moisture and is widely used in both field and laboratory. In a system where rapid and/or continuous changes in moisture content and soil moisture tension occur, any appreciable exchange of water between soil and tensiometer hinders the establishment of the required equilibrium and distrubs the system.

In 1951 Miller (34) introduced a new form of tensiometer making it possible to eliminate lag and lessen the amount of water transferred. He used a manually controlled water manometer and a sensitive null indicator to enable the person to observe the correct manometer setting.

Leonard and Low (23) described the design and experimental data for a tensiometer which included both the null point and self-adjusting features. The moisture tensions measured by this instrument were slightly less than those measured by the conventional tensiometer. The difference increased with increasing tension, but, except at low tensions, did not exceed 2%.

Bianchi (2) constructed an instrument that transformed a change in soil moisture tension into an electrical resistance change. A metal diaphragm instrumented with a resistance strain gauge was substituted for the gauge or manometer of the conventional tensiometer. The strains in the diaphragm induced by the pressure were transformed into resistance changes which were recorded.

Huggins (19) described an instrument which measured very small pressure change that could not be readily detected by a manometer. The transducer was based on the principle of the measurement of deflections at the center of a thin circular diaphragm. When a pressure differential was applied the deflections were measured by a linear variable differential transformer which produced an output voltage directly proportional to the displacement of a separate, moveable core.

Klute and Peters (20) used a strain gauge diaphragm type of pressure transducer in order to keep the pressure change per unit volume change of the tensiometer as large as possible.

Thiel and co-workers (45) described an electrical water pressure transducer which was designed and constructed for the purpose of measuring hydrostatic pressures in porous media. The instrument employed a stainless steel sensing diaphragm and a linearly variable differential transformer as a deflection senser.

III. MATERIALS AND METHODS

A. Materials

In this study graded silica sands were used. These sands were available in a range of particle sizes. The material was reasonably uniform in shape and the individual particles were clean and hard. The commercial grades and equivalent particle size distributions, as determined in the laboratory, are shown in Table 1. The texture of the sand separates ranged from very fine sand to gravel. The bulk density ranged from 1.33 to 1.58 g/cc with the bulk density increasing with increase in particle size. The particle density of the sand separates were similar. The average particle density was 2.75 g/cc. The percent total porosity of the separates decreased with increasing particle size. Throughout the thesis, these sand separates will be referred to by the average particle size. It should be remembered that some of the separates have a rather wide size range and some overlap.

B. Methods

1. Moisture tension curve

Samples of the air dry sand separates were placed in a metal cylinder three inches in diameter and three inches

Table 1. Physical properties of the sand separates.

Commercial grade	Manu-facturer's size-mm. dia.	Avg. particle size mm. dia.	Percent particle size distribution--mm. dia.						Bulk density g/cc	Particle density g/cc	Total porosity %
			4.0-2.0 gravel	2.0-1.0 V.C. sand	1.0-0.5 C. sand	0.5-0.25 M. sand	0.25-0.1 F. sand	0.1-0.07 V.F. sand			
½	0.21/0.125	0.17				0.4	95.3	4.2	1.33	2.76	48.6
1	0.3 /0.15	0.23			0.1	26.8	72.9	0.2	1.37	2.74	49.7
2	0.5 /0.25	0.38			63.2	34.1	2.5	0.1	1.47	2.78	47.7
3	0.84/0.42	0.63		0.2	99.0	0.6	0.1		1.51	2.78	46.2
4	1 /0.59	0.8		59.6	40.3	0.1			1.55	2.74	43.5
7	1.68/1.0	1.34		99.6	0.3	0.1			1.56	2.75	43.5
8	3 /1.4	2.2	99.9						1.57	2.79	43.5
9	4 /1.68	2.84	100.0						1.58	2.78	42.3

long. A piece of filter paper covered the bottom and was held in place by a double layer of cheesecloth which was stretched across one end of the cylinder and secured with a rubberband.

Four hundred grams of each sand separate were poured into the cylinder and tamped by tapping on the table 10 times from a height of 5 cm. The surfaces of the samples were leveled and triplicate samples were saturated for 24 hr by placing them in a pan containing distilled water.

A similar procedure was followed in the preparation of layered samples by pouring 200 g for the first layer, leveling the surface, then adding 200 g for the second layer and then tapping the core on the table 10 times.

Moisture tension curves and bulk densities were obtained from weight loss measurements which were made after equilibrium was established on tension tables similar to those described by Leamer and Shaw (21). The measurements were made at 5 cm intervals from 0-60 cm tension.

2. Capillary rise

Plexi-glass tubes 2 cm inside diameter and 50 cm long were covered at the bottom with filter paper which was held by cheesecloth. Because of the importance of uniform packing in capillary rise studies, the sand separates were put into the tubes in a way similar to one used by Miller (29) in which a plastic extension tube of 2 cm inside diameter and 10 cm in length was attached to the top of the sample tube. A plastic funnel with a stem of 1.5 cm diameter and of sufficient length to reach the bottom was placed inside the sample and extension tube. An amount of sand separate sufficient to fill the sample tube was poured rapidly into the funnel. The funnel was slowly withdrawn from the tube leaving a uniformly packed tube of sand separates. The tubes, in triplicate, were then tamped by tapping on the desk 10 times from a height of 5 cm. The samples were placed in a tray containing 1.0 cm of water which was maintained constantly throughout the experiment. The capillary rise of water was measured for each separate at 0.5, 2, 4, 12, 24, 48, 72 and 96 hrs at $21 \pm 2^{o}C$ temperature and relative humidity of 35-40%.

3. Water infiltration

These experiments were carried out at constant temperature of $21 \pm 2^{o}C$ and relative humidity of 35-40%. In this study, both uniform and layered columns of sand material were used to simulate stratified soil profiles in the field.

Rigid transparent plastic cylinders 70 cm long and 12 cm in diameter were fitted with tensiometers through holes drilled in the walls of the cylinders. These tensiometers were coarse fritted glass, gas dispersion tubes 1.2 cm in diameter and 2.0 cm. long and had air entry values of 58 ± 1 cm of water. All tensiometer connections were sealed with Duco-Cement. There was a minimum of three tensiometers in each cylinder. The first was located above the stratum, the second at the center of the stratum and the third one below the stratum.

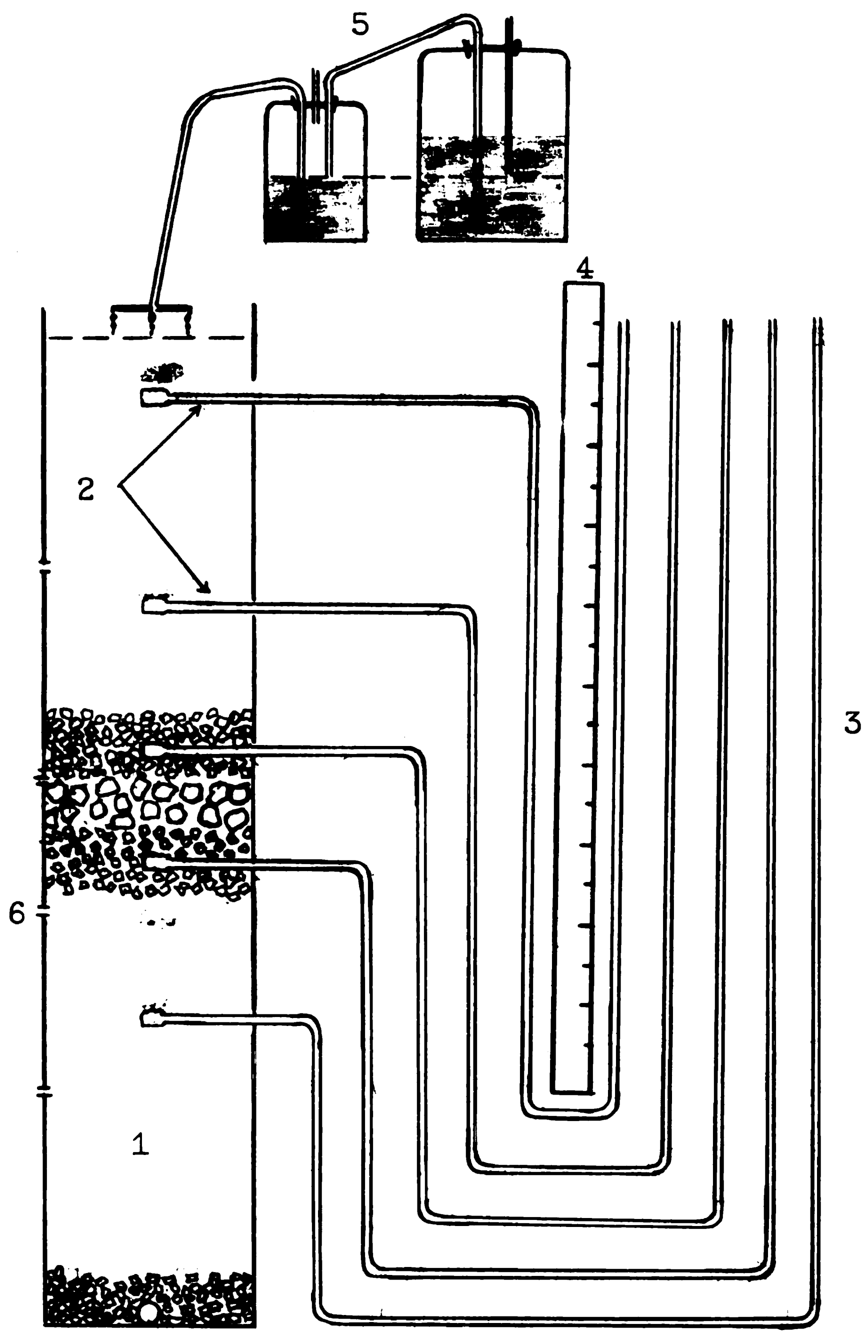
After preparation of the columns, the tygon tubes from the tensiometers were arranged on a board with a meter stick to form the manometers. Several holes were drilled in the cylinder wall opposite the tensiometers to facilitate air escape. Figure 1 is a diagram of the experimental set-up.

The plastic cylinder was filled with distilled water. The tensiometers and the tension measuring device were filled with water and checked to be free of air. The column was placed on a mechanical sieve shaker which simultaneously rotates and vibrates the column. A 2 mm sieve was attached to the top of the column, and the air dry sand separate poured through the sieve at a constant rate until the column was full during which time the column was vibrated and rotated slowly. Any extra sand was removed and the surface was leveled.

In the case of the stratified columns, the bottom layer was prepared as outlined above. After leveling the surface of the bottom layer, the material to form the next layer was poured on the top of the first strata in the same way and leveled. In three layered soils this was repeated.

Figure 1. Schematic diagram of experimental setup for water manometer technique.

1. Uniform or stratified sand column.
2. Tensiometers.
3. Water-manometer for direct measuring of moisture tension.
4. Meter-stick for measureing a change in moisture tension in sand column.
5. Constant head water supply.
6. Air escape opening.


5
4
2
3
6
1

4. Moisture tension distribution

Two different methods of measuring soil moisture tension were used: (a) water manometer technique and (b) pressure transducer technique.

The basic difference between the two methods is that the manometer depends on an exchange of water between soil and tensiometer which requires time to come to equilibrium, and also influences soil moisture content. On the other hand, the tensiometers used with the pressure transducer acted as a null-type tensiometer with little exchange of water between the tensiometer and the soil. This method is fast and has little influence on the soil system.

a. Water manometer technique

The tensiometers were connected to tygon tubes that were arranged on a board with a meter stick and acted as a water manometer.

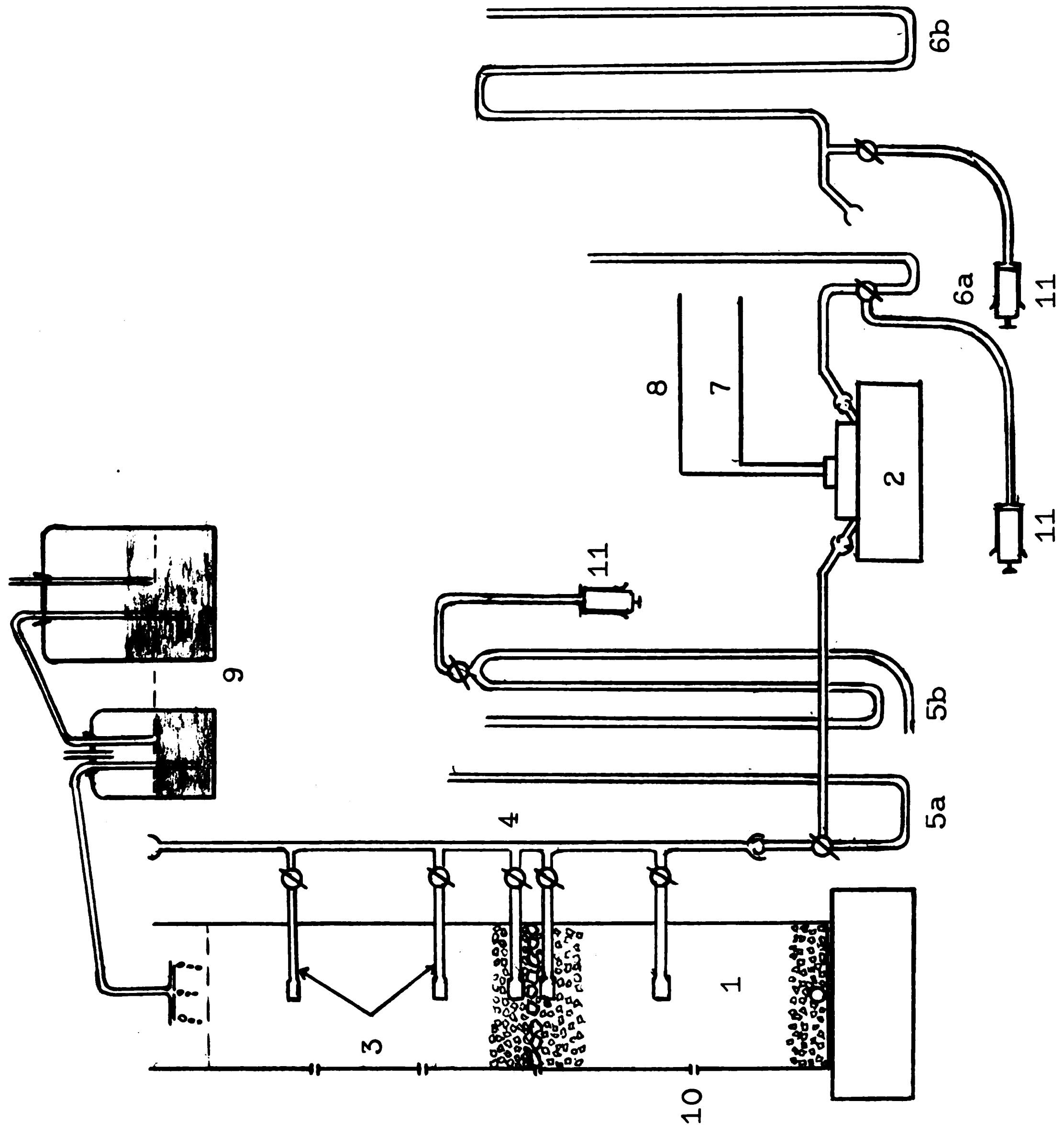
The sample was left to drain for 24-48 hrs until the flow of water stopped. The system was assumed to be at equilibrium and the tension referred to as initial tension under static condition.

b. Pressure transducer technique

The experimental set-up with the pressure transducer was arranged in the same way as shown in Figure 2 except that each tensiometer had a teflon stopcock which allowed the measurement of each tensiometer separately and at any time.

Figure 2. Schematic diagram of the experiment - Pressure transducer technique.

1. Uniform or stratified sand column.
2. Pressure transducer.
3. Tensiometers.
4. Hydraulic connection between the recording side of the transducer and the tensiometers in the sand column.
5. Water-manometer connected to recording side of the transducer for calibration with applied 5a) positive pressure and 5b) positive or negative pressure.
6. Water-air manometer connected to reference side of the transducer for calibration with applied 6a) positive pressure and 6b) positive or negative pressure.
7. Power supply to the pressure transducer - 6V dry cell battery.
8. Electrical connection to the recorder.
9. Constant head water supply.
10. Air escape opening.
11. Syringe pump for adjusting reference pressure.


1
2
3
4
5a
5b
6a
6b
7
8
9
10
11
11
11

A water manometer was connected to the hydraulic connection with a 3-way stopcock and was used for calibration of the instrument.

The reference side of the transducer either was left open to the atmosphere or to the air-water manometer for calibration and extension of the tension range.

A Dynisco strain gauge differential pressure transducer PT 14-01, which is shown in Figure 3, was used in these experiments. This transducer had two ¼-inch diameter flared tubing pressure fittings; one connecting to the reference pressure side of the internal diaphragm. The second fitting was connected to the bottom chamber of the case which also held the strain gauge .

The reference side of the pressure transducer could be left open to the atmosphere for absolute reading of the pressure at the recording side. A positive or negative pressure could be used in the reference side to obtain differential pressure in respect to the recording side.

The strain gauge sensing elements of the pressure transducer contained four active strain gauge arms wired in the configuration of a wheatstone bridge, (figure 4). Power for the bridge circuit in the transducer was obtained from dry cell batteries supplying 6-V. The output of the transducer was about 1.48 mv/cm of water when the applied bridge voltage was 6-V.

Figure 3. General features of the pressure transducer.

a. Reference side.

b. Recording side.

c. Adapters.

d. Electrical connection.

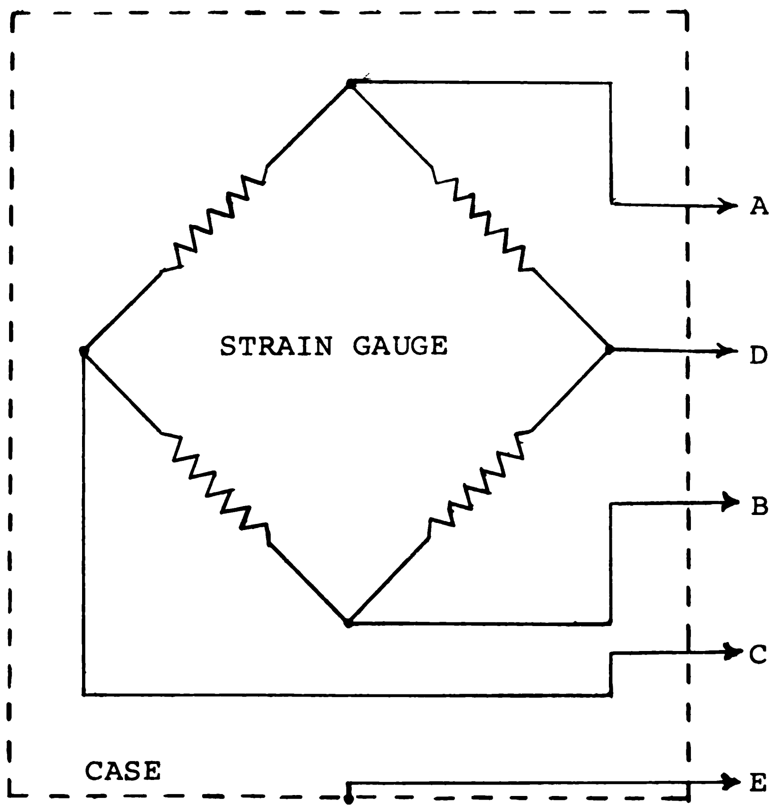


Figure 4. Electrical circuit of strain gauge.

A = Signal (+)

B = Signal (-)

C = Exitation (-)

D = Exitation (+)

E = Ground (case)

The recorded pressure, in millivolts per centimeter of water was a result of the reaction of a stainless steel diaphragm located inside the pressure transducer to an applied pressure. The applied pressure could be either from the reference side or from the recording side of the transducer.

At the start of each experiment, a working curve (Figure 5) for the pressure transducer was obtained by applying increments of positive pressure to the recording side of the transducer while the reference side was left open to the atmosphere. To show the reversibility of the diaphragm, an increment of negative pressure was applied to the reference side while the recording pressure side was kept at atmospheric pressure. The data obtained were identical for both cases, and were plotted as centimeters of height versus millivolts of output. The graph was used as a standard curve to convert the millivolt reading to tension in centimeters of water.

Because the voltage of the batteries changed with continuous use, there was a shift in the position of the standard curve, i.e. decrease in the output per centimeter pressure applied. For this reason, a new standard curve was necessary each day.

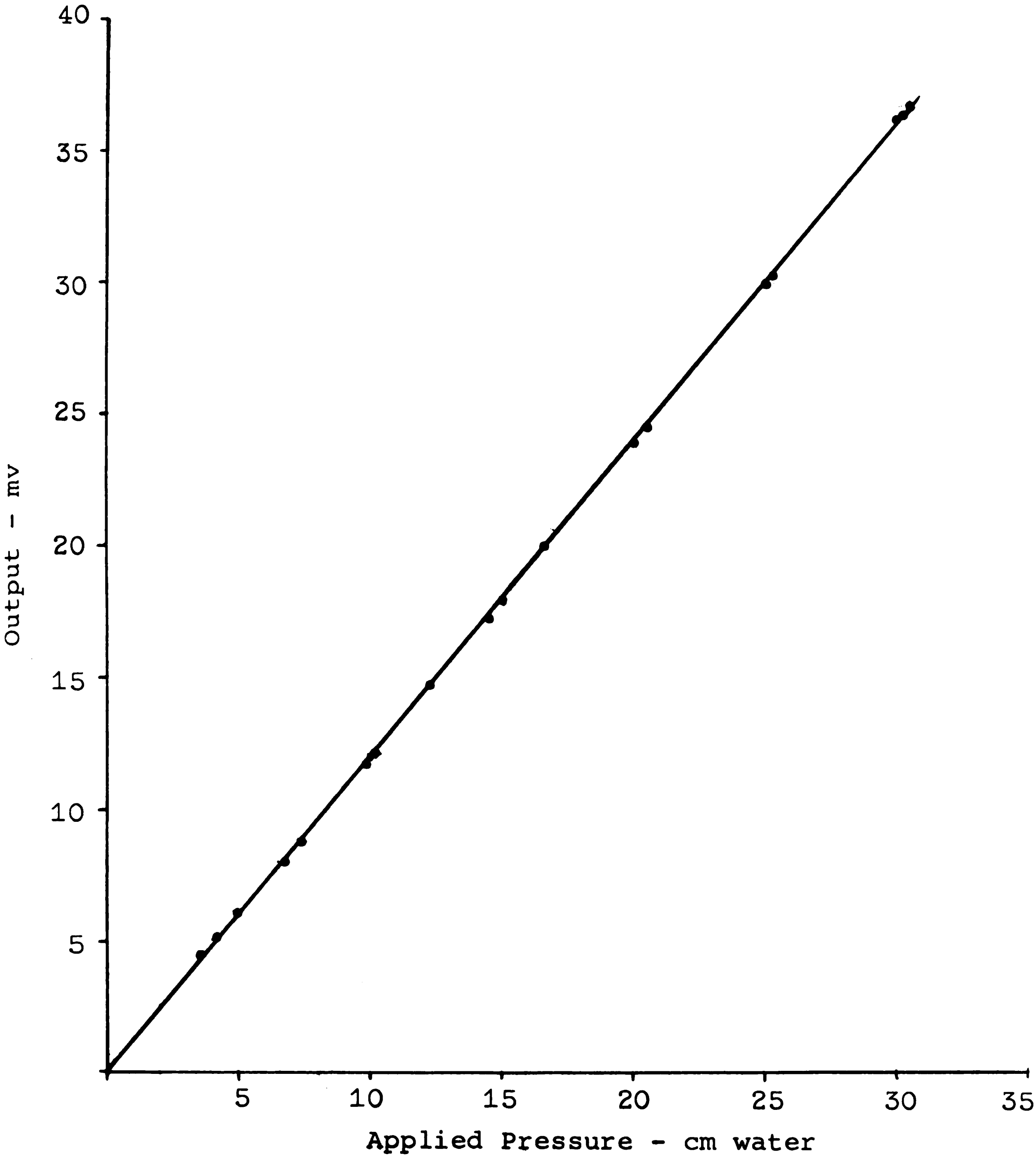


Figure 5. Calibration curve when positive pressure was applied to recording side of the transducer and the reference side was at atmospheric pressure.

5. Water application and recovery

In the preliminary studies with the water manometer, one constant rate of water application was used. Two hundred milliliters of distilled water was added uniformly at 3 min intervals to the surface of the column. The surface of the columns was always protected by a covering of filter paper or a thin layer of a gravel.

Different rates of water application were used with the pressure transducer. These rates varied from 60 cc/min to as low as 0.025 cc/min. The rate of water application was adjusted by varying either the diameter of the capillary tube leading to the hypodermic needle, or the head of water above the column. This rate was kept constant during any given experiment.

The time of the first discharge of water was recorded, and periodically, the volume of discharged water recorded. From these, the volume of water applied and recovered was determined.

At the end of the experiments, the sand columns were sampled and moisture content was determined gravimetrically, which gave a general idea of the moisture distribution in the column.

IV. RESULTS

A. Moisture-tension characteristic curves

In this study seven silica sand separates were used. Moisture tension curves were determined on 3-inch diameter cylinders containing uniform and different layers of sand separates. Various arrangements of the fine and coarse layers were used. The measurements were made at 5 cm intervals from 0 to 60 cm of tension with the samples kept for 24 hrs at each tension. After the final tension measurements had been made, the layers of sand were separated and the amount of moisture was determined in each layer.

The data presented in in Tables 26 through 31 in the appendix and Figures 6 and 7 show the percent moisture on weight basis for each of the uniform and the layered sand separates.

The data in Figure 6 have the characteristic form of moisture desorption curves for the uniform sand separates. The percent of moisture increased as the particle size of the separates decreased. The tension required to drain the pores in the sand separates increased with decreasing particle size. The data also show that the separates 0.63 mm and greater came to approximately the same final moisture

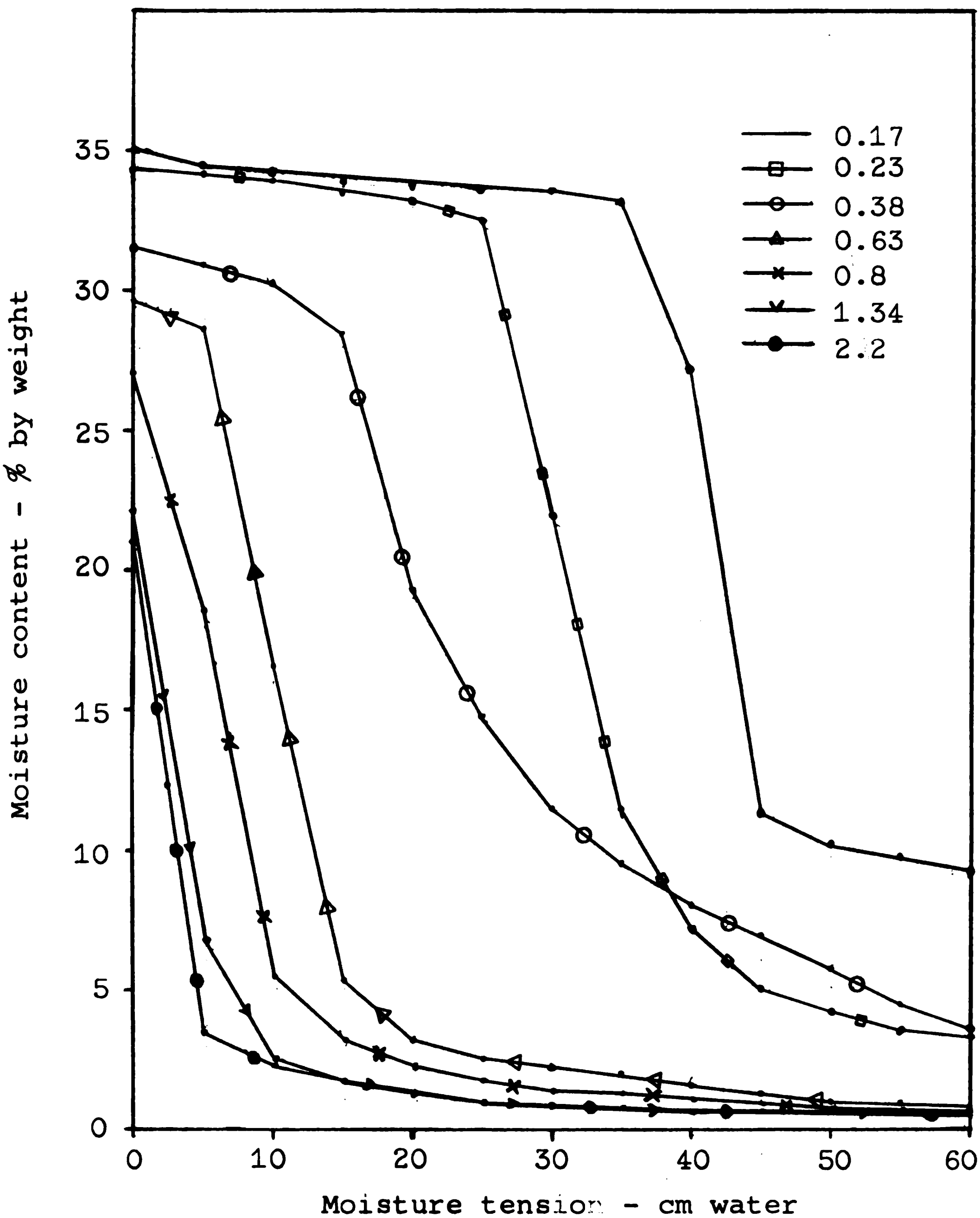


Figure 6. Moisture - tension curves for uniform sand separates.

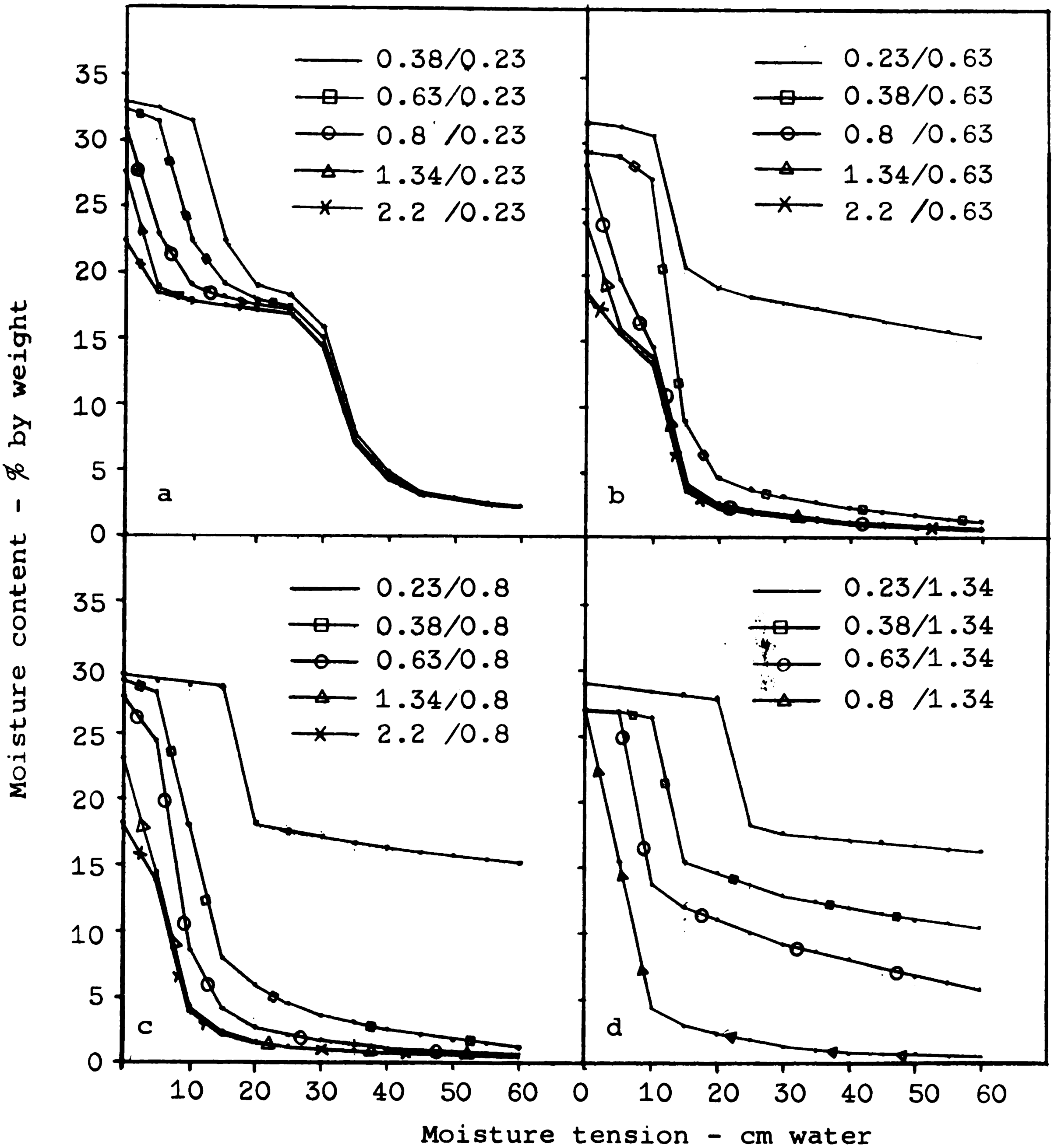


Figure 7. Moisture - tension curves for 2-layered sand separates.

content. Sand separates with 0.17 and 0.23 mm average particle diameter had higher moisture contents because they were not completely drained at 60 cm tension, meanwhile there was an overlapping of data in sand separates 0.23 and 0.38 mm in average particle diameter, because of the wide range of size distribution of both sands.

The moisture tension curves for layered cores in Figure 7 indicate the presence of two breaks in the moisture tension curves. The breaks become more pronounced the greater the difference in particle size distribution of the two layers. When the coarse sand separate was underlying fine textured sand, there was no significant amount of water removed from the fine sand layer until the tension necessary to drain the fine layer was reached. However, after approaching this critical point, a small increase in tension caused removal of a large amount of water from the sample due to draining both layers at once. When the fine sand was underlying the coarse sand, the coarse layer drained out through the fine layer at almost its normal tension, then the bottom fine layer drained when the tension was raised.

The results of the experiments indicate that it was necessary to bring each sand separate to a certain critical tension before a significant amount of water was removed from the system. The tension required to reach the breakpoint increased with decrease in particle size (37). This fact was very evident with the uniform sand separates and when a fine sand was underlain by coarse sand separates.

The moisture distribution in the layered sand cores indicated the presence of a large amount of water in the fine layer overlying the coarse layer. The moisture content was 75% higher when the fine sand, of 0.23 mm average particle size, was underlain by a very coarse sand of 1.34 mm in diameter (1, 31 and 32).

The data presented here represent soil moisture characteristics of sand separates ranging from fine sand up to gravel. The maximum tension required for the fine sand to drain and have moisture tension discontinuities was 45 cm of water. This indicates that in sand soils, under field conditions, the movement of water falls to its minimum at 60 cm tension or less. There is also no appreciable amount of water left in these sand separates. The above relationships will hold true in all sandy soil unless the soil profile is stratified.

This and previous work in relation to availability of moisture in sandy soils (7, 14) emphasize again the importance of soil texture in determining moisture holding capacity, available moisture to plants and irrigation requirements. For example, the early concepts of field capacity excluded from generalization those soils which contained plow pans or clay pans which are known to restrict downward flow of water. But textural changes or discontinuities in the profile were thought not to affect flow seriously and were usually disregarded in describing field capacity.

From this study and the subsequent studies reported here, the presence of any kind of stratification greatly influences water flow and field capacity. For this reason, field capacity should be considered as a soil profile function rather than a property of soil only in the root zone or plow layer.

B. Capillary rise

1. Capillary rise of water in uniform sand separates

Data presented in table 2 illustrate that capillary rise of water increased with decrease in particle size which is reported elsewhere (3, 24, 7). The highest capillary rise was with average particle size of 0.17 mm in diameter. The data also show that the maximum rate of capillary rise occurred within the first period, after which the rate of capillary rise slowed down.

2. Capillary rise of water in layered sand separates

This experiment was designed to illustrate the effect of stratification on height of capillary rise of water. Height of capillary rise with time was determined in columns with (1) coarse sand under fine sand and (2) fine sand under coarse sand. Sand with average particle sizes of 0.72 mm and 0.17 mm were used for coarse and fine layers respectively.

Table 2. Capillary rise of water in 8-uniform sand separates at different times after the start.

Particle size mm	Time of measurement - hr after start								
	0.5	1	2	4	12	24	48	72	96
	Capillary rise - cm								
0.17	27.7	30.7	32.5	34	35.8	37.0	37.5	38.0	38.4
0.23	16.5	17.4	18.1	19.1	20.7	21.4	22.8	23.4	23.9
0.38	7.3	8.6	9.6	10.3	10.6	11.3	12.4	13.3	13.6
0.63	6.0	6.2	6.5	6.7	7.0	7.3	7.5	7.8	7.8
0.8	5.5	5.7	5.9	6.0	6.3	6.6	7.0	7.2	7.4
1.34	4.7	4.8	4.9	5.2	5.4	6.0	6.3	6.4	6.5
2.2	4.1	4.2	4.5	4.8	5.0	5.2	5.3	5.3	5.5
2.84	3.6	4.0	4.5	4.7	4.9	5.1	5.2	5.3	5.4

According to the data presented in Table 3, the relationship of height of capillary rise in stratified sand did not have the same characteristics that were observed in uniform textured sand. On the contrary, there were breaks, the location of which was related to the particle size and the height of the boundaries of the layers.

These breaks were evident in the capillary rise of water in sands with a coarse layer underlying a fine layer. In these cases the height of capillary rise was dependent on maximum capillary rise of the coarse sand. If the fine sand boundary was less than the maximum capillary rise of the coarse sand, the coarse sand was completely wetted and the fine sand wetted to its characteristic height of capillary rise. If the coarse layer was thicker than the characteristic capillary rise of the coarse sand, the coarse sand wetted to this height and the upper layer remained dry. In the case where the coarse sand layer was 5 cm thick, which is close to the 5.4 cm maximum capillary rise, the fine sand did not wet until after three hours which was the time required for the 5 cm thick coarse sand to wet to this height. Once the boundary of the fine sand was reached this layer rapidly conducted water to its characteristic height of capillary rise of around 40 cm.

In stratified columns where a fine layer was under a coarse layer, there was no capillary rise in the coarse layer when the thickness of the fine layer was beyond the

Table 3. Capillary rise of water in cm. in 2-layered sand columns at different times after start.

Avg. particle size of bottom layer	Height of bottom layer	Avg. particle size of top layer	Time of measurement-hr after start 5 Min	10 Min	15 Min	30 Min	1 hr	2 hr	4 hr	24 hr	96 hr	192 hr
mm	cm	mm	Capillary rise-cm.									
0.72	40	0.17	3.8	3.9	3.9	4.0	4.1	4.4	4.9	5.0	5.2	5.4
0.72	10	0.17	3.8	3.9	4.0	4.1	4.3	4.4	4.8	5.0	5.2	5.4
0.72	5	0.17	3.7	3.9	4.0	4.1	4.3	4.4	27.0[1]	34.8	38.0	38.8
0.72	3	0.17	15.1	19.5	23.7	27.0	30.5	33	35.0	39.0	42.0	43.3
0.17	50	0.72	17.5	21.7	24.0	27.7	30.7	32.5	34.0	37.0	38.4	39.3
0.17	20	0.72	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
0.17	10	0.72	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
0.17	5	0.72	5.0	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.2	5.3
0.17	3	0.72	4.5	4.6	4.6	4.7	5.0	5.1	5.2	5.6	6.0	6.4
0.17/0.72/0.17	5 + 1 + 34		5.0	5.0	5.1	5.1	5.1	5.1	5.2	5.2	5.2	5.4

[1]At the end of 3 hr. the water moved to the fine layer.

maximum height of capillary rise in the coarse layer. But when the thickness of the fine layer was within the maximum capillary rise of the coarse layer, the capillary rise was continued in the coarse layer above the fine layer. Furthermore the height of the capillary rise was higher in the coarse layer over the fine layer compared to uniform coarse sand but this is probably a packing effect.

In the stratified sand column where a 1 cm coarse stratum was interposed in a column of fine sand at a height of 5 cm, the capillary rise of water reached only 0.4 cm into the coarse layer. This height was similar to the capillary rise in uniform coarse sand.

These experiments show that the height of capillary rise in a stratified sand column will be governed by either the maximum height capillary rise in a particular separate or by the lower boundary of a coarse sand layer provided the height of this layer is above maximum capillary rise of the coarse sand and below that of the fine bottom layer of the column.

From the above observations it is indicated that a restriction of capillary rise can occur in a stratified sand column whether a coarse layer was over or under a fine layer and suggests the importance of coarse sand layers in the restriction of capillary rise.

The increase in capillary rise in the fine layer overlying a coarse layer was suggested by Felitsiant (10,11) as being due to the force of air friction on the soil particles when displaced by the capillary rise of water. However, the experimental procedure of the present study where the bottom layer was packed twice may have caused a difference in bulk density of the two layers and consequently may have contributed to the increased capillary rise in these columns.

C. Moisture tension distribution during water flow

1. Water manometer technique

A series of preliminary experiments were performed to evaluate the movement of water in stratified sand columns. For this purpose the following experimental systems were used: (1) uniform sand columns, (2) 2-layered columns where a fine sand overlay coarse sand, and (3) 3-layered sand columns where a coarse layer of 4 cm thickness was placed between two layers of fine sand. The height of the column was 60 cm in all cases unless otherwise specified. Because of the preliminary nature of these experiments, only one rate of water application was used.

Moisture tension distribution and flow of water out of the column was measured. The moisture tensions observed describe only the wet front movement of the water as the duration of water application was not long enough to bring the tension at different parts of the column to steady state condition. For this reason, attention will be given to the moisture tension distribution in the static state condition (point in time when the column ceased to drain and no water movement in the column occurred), either initially or after water application. These data represent an average of more than five runs in each case.

a. Moisture tension distribution in uniform sand columns

Uniform columns, 60 cm high, with tensiometers located at 15, 30, and 45 cm from the bottom were prepared for the following sand separates:

Column	Particle size range-mm dia	Average size - mm
1	0.3 - 0.15	0.23
2	0.5 - 0.25	0.38
3	0.84 - 0.42	0.63
4	1.0 - 0.59	0.8
5	1.68 - 1.0	1.34
6	3.0 - 1.4	2.2
7	4.0 - 1.68	2.84

Moisture tension distribution under static condition and moisture content for each column are shown in tables 4, 5 and figure 8. Each sand column has a characteristic pattern of changing moisture tension and moisture content through the column. Moisture tension decreases from the surface to the bottom of the column in each sand separate.

Table 4. Moisture tension distribution in uniform sand columns under static conditions.

Tensiometer height-cm from bottom	Avg. particle size of column - mm dia						
	0.23	0.38	0.63	0.8	1.34	2.2	2.84
	Moisture tension - cm water						
45	42.7	29.7	25.5	20.1	12.3	9.6	7.6
30	29.5	23.2	19.6	17.0	10.5	7.7	5.5
15	14.5	13.8	13.9	13.1	8.6	6.4	4.2

Table 5. Distribution of moisture in uniform sand columns under static conditions.

Locations of samples - cm from bottom	Avg. particle size of column - mm dia						
	0.23	0.38	0.63	0.8	1.34	2.2	2.84
	Moisture content - % by weight						
45	7.8	3.4	3.9	2.7	2.4	2.7	2.8
30	15.7	4.0	4.0	3.0	3.0	2.7	2.8
15	24.9	19.4	10.5	4.0	3.0	3.1	3.3
	Depth to which bottom appeared saturated - cm						
	30.0	17.0	12.0	7.0	5.0	3.5	3.0

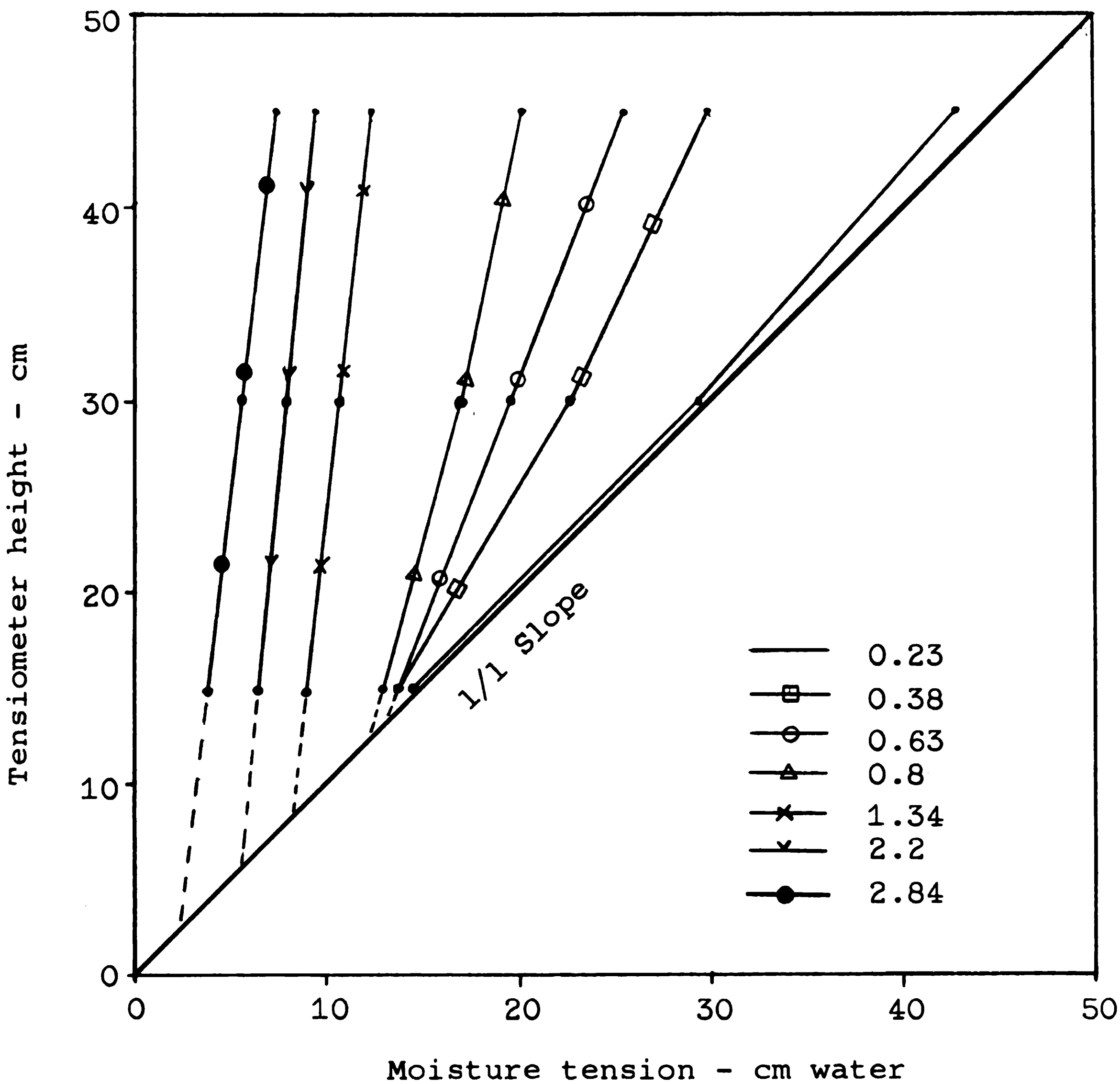


Figure 8. Moisture tension profiles of uniform sand columns under static conditions.

The change in moisture tension with height in fine sands is very close to unity, but as the particle size of the separate was increased, moisture tension changes with height became less than unity. In all columns there was an increase in moisture content at the bottom of the column. The height of the apparent saturated zone was increased with a decrease in particle size of the column and was the highest with fine textured column. The decrease in the water holding capacity with increasing pore size aided in draining the coarse textured column at low tension and less water accumulation at the bottom of the column. Furthermore, in the fine textured sand where the pore size decreased, a higher tension was required to drain the column.

If the values of moisture tension in the column were extrapolated to a zero height, this value intersects a 1/1 slope at a certain value. This value is closely related to the height of the accumulated water at the bottom of the column and also is equivalent to the maximum height of capillary rise for the same sand column plus the extra height due to hysteresis. The fact that the lower wall of the tensiometer was at 14.5 cm from the bottom and 0.23 mm dia sand data had a point at 14.5 cm indicated the tensiometers were functioning properly.

b. Moisture tension distribution in layered sand columns

(1) 2 - layered sand columns

Tensiometer readings were made at heights of 15, 25, 30, and 45 cm from the bottom of 56 cm columns in which a layer of fine sand was over an equal layer of coarse sand. Seven different combinations of particle size were studied:

Column	Top 28 cm	Bottom 28 cm
	Average particle size - mm dia	
1	0.23	0.8
2	0.23	1.34
3	0.38	1.34
4	0.63	1.34
5	0.63	2.2
6	0.38	2.84
7	0.8	2.84

At the end of the experiments, samples from the level of each tensiometer were taken for moisture determinations.

The results of the experiments are presented in tables 6 and 7 and in figure 9. In all systems, a marked effect of the coarse textured layer on moisture tension as well as moisture distribution was expressed. The magnitude

Table 6. Moisture tension distribution in 2-layered sand columns under static conditions.

Tensiometer height from bottom - cm	Average particle size of sand layers-mm dia						
	0.23/0.8	0.23/1.34	0.38/1.34	0.63/1.34	0.63/2.2	0.38/2.84	0.8/2.84[1]
	Moisture tension - cm water						
45	32.6	27.4	25.1	24.3	22	23.9	14.9
30	17.6	12.7	10.2	12.5	10.9	8.0	7.9
25	13.6	9.8	9.2	9.0	6.8	5.5	5.7
15	10.7	8.6	8.4	8.6	5.7	4.9	5.0

[1]Average particle size of top layer/ Average particle size of bottom layer.

Table 7. Moisture distribution in 2-layered sand column under static conditions.

Location of the samples - cm from bottom	Average particle size of sand layers-mm dia					
	0.23/0.8	0.23/1.34	0.38/1.34	0.63/1.34	0.38/2.84	0.8/2.84
	Moisture content - % by weight					
45	17.3	20.2	4.3	3.0	3.7	2.6[1]
30	32.3	32.4	27.2	16.4	22.5	14.2
15	5.8	3.3	4.4	4.4	3.3	3.7

[1]Average of five or more samples.

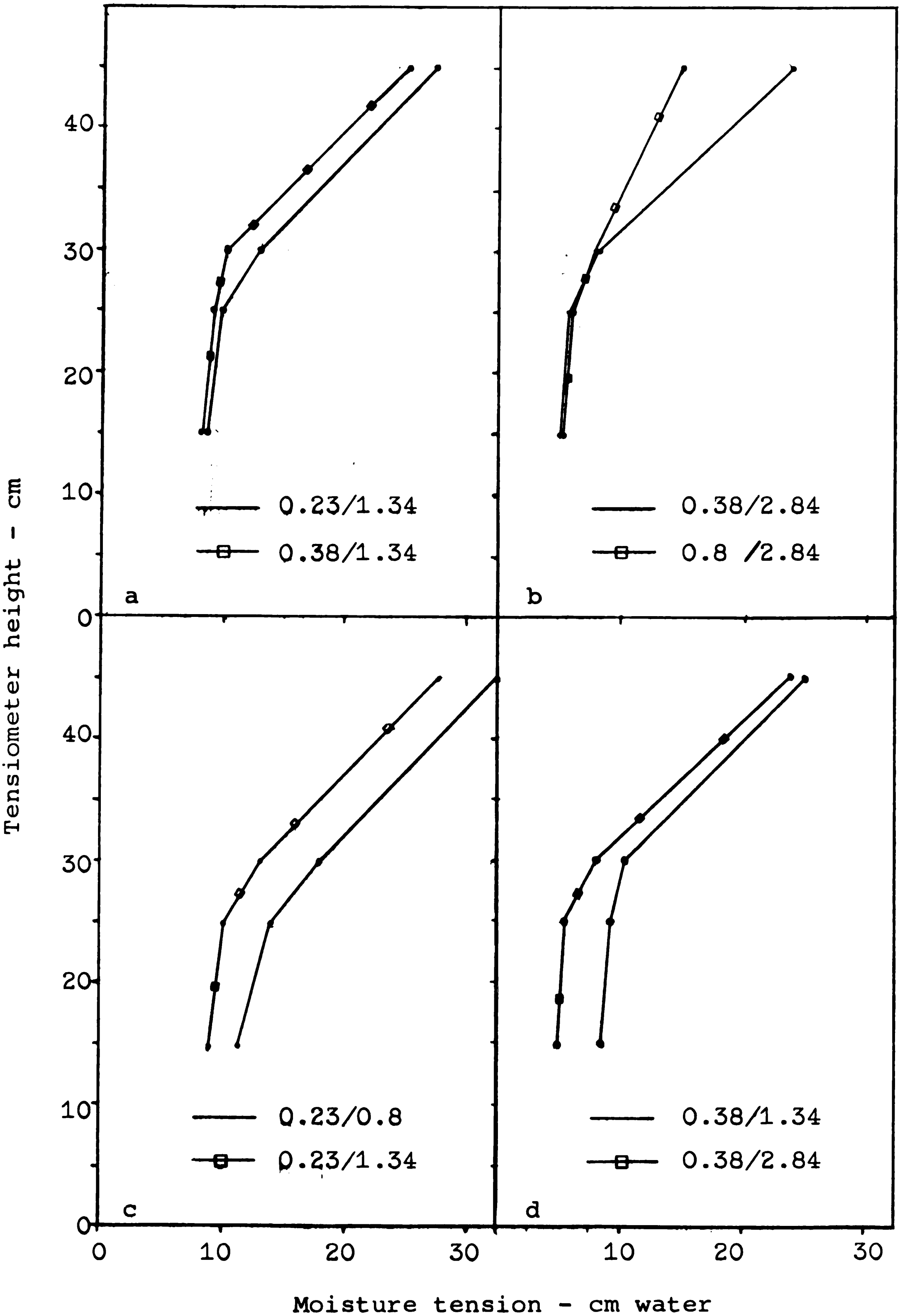


Figure 9. Moisture tension profiles of 2 - layered sand columns under static conditions.

of this effect was dependent on the combination of the particle sizes of the two layers forming the column.

In all the columns investigated, there was a decrease in the moisture tension in the fine sand above the coarse layer as compared to the moisture tension at the same height in the uniform fine sand separates. The moisture content at the bottom of the fine layer above the coarse layer was much greater in all the columns than at the same depth in uniform columns of the same particle size (tables 6 and 7). The increase in moisture content above the coarse layer in the layered column compared to the uniform column of the same particle size, varied from 11% to 23%. The increase in moisture content was the highest in the column with particle size of 0.38 mm over 1.34 mm in diameter.

In a study of capillary rise Stapren (43) suggested that the maximum height of accumulated water above the coarse layer was equal to the difference between the capillary rise for individual sand separates composing the column. Similar data (table 8) were obtained in this study where the height of accumulated water above the coarse layer is very close to the difference in values of capillary rise of the two separates.

Several comparisons can be made as to effect of particle size of upper fine layer or coarse bottom layer on distribution of moisture tension through the column. Comparing moisture tension distribution in columns of fine sand

Table 8. A comparison of the difference in capillary rise between the two sand separates forming the 2-layered sand column and the height of accumulated water above the coarse layer in the same column.

Particle size-mm		Max. cap. rise of each separate-cm		Difference in cap. rise of two separate-cm	Height of water accumulated above the coarse layer-cm
Top layer	Bottom layer	Top	Bottom		
0.23	0.8	23.9	7.4	16.5	14.0
0.23	1.34	23.9	6.8	17.1	14.5
0.38	1.34	13.6	6.4	7.4	8.0
0.63	1.34	7.8	6.5	1.3	1.5
0.63	2.2	7.8	5.5	2.3	2.5
0.38	2.84	13.6	5.4	8.2	6.5
0.8	2.84	7.4	5.4	2.0	2.5

over coarse sand where the particle size of the upper layer changes only, the data in figure 9a and 9b shows no change in moisture tension in the bottom layer which is the same in each case while there is a decrease in moisture tension above the coarse layer which depends on the particle size of the fine top layer.

However, when the particle size of the coarse bottom layer is changed (figure 9c and 9d) the distribution of moisture tension in the lower layer is different. The moisture tension values at the bottom of the fine layer is different but the moisture tension distribution has the same slope.

(2) 3 - layered sand column

Moisture tension readings were made at heights of 15, 28, 32.5, 35 and 45 cm from the bottom of 60 cm columns. A 4 cm thick coarse stratum was interposed at a height of 30-34 cm. Four different combinations of particle size were studied.

Top 26 cm	Interposed 4 cm coarse stratum	Bottom 30 cm
	Average particle size - mm dia	
0.38	1.34	0.38
0.63	1.34	0.63
0.38	2.2	0.38
0.63	2.2	0.63

The results of the experiments are presented in table 9. A pronounced effect of the coarse layer on the distribution of moisture tension was observed in all systems.

The four columns were compared as to effect of particle size of the interposed coarse stratum and the particle size of the whole column on the change and discontinuity of the moisture tension distribution through the columns in figure 10. The change in moisture tension distribution across the stratum followed the order 0.38 / 2.2 / 0.38 > 0.38 / 1.34 / 0.38 > 0.63 / 2.2 / 0.63 > 0.63 / 1.34 / 0.63. Thus the greater the difference in particle size between the layers, the greater was the magnitude of the discontinuity.

A set of three columns was prepared to evaluate further the effect of particle size of the interposed coarse strata on a moisture tension distribution in a column of very fine sand. Tensiometer readings were made at heights of 25, 32.5, 35 and 45 cm from the bottom of 60 cm columns in which a 4 cm thick coarse strata was interposed on the column of fine texture at a height of 30-34 cm. Three different particle sizes in the strata were used.

Top 26 cm	Interposed 4 cm coarse stratum	Bottom 30 cm
0.17	0.38	0.17
0.17	0.63	0.17
0.17	0.8	0.17

Table 9. The effect of particle size of the interposed coarse stratum on moisture tension distribution in 3 - layered sand column of different body texture under static conditions.

Height of tensiometer from bottom - cm	Average particle size of columns - mm dia[1]			
	0.38 / 2.2 / 0.38	0.63 / 1.34 / 0.38	0.63 / 2.2 / 0.63	0.63 / 1.34 / 0.63
	Moisture tension - cm water			
45	19.5	20.1	20.7	20.5
35	9.0	10.0	10.2	10.8
32.5	6.3	8.6	8.1	8.5
28	23.6	22.9	21.6	20.1
15	14.6	14.4	14.7	14.4

[1]Average particle size of top layer / Average particle of the interposed stratum / Average particle size of bottom layer.

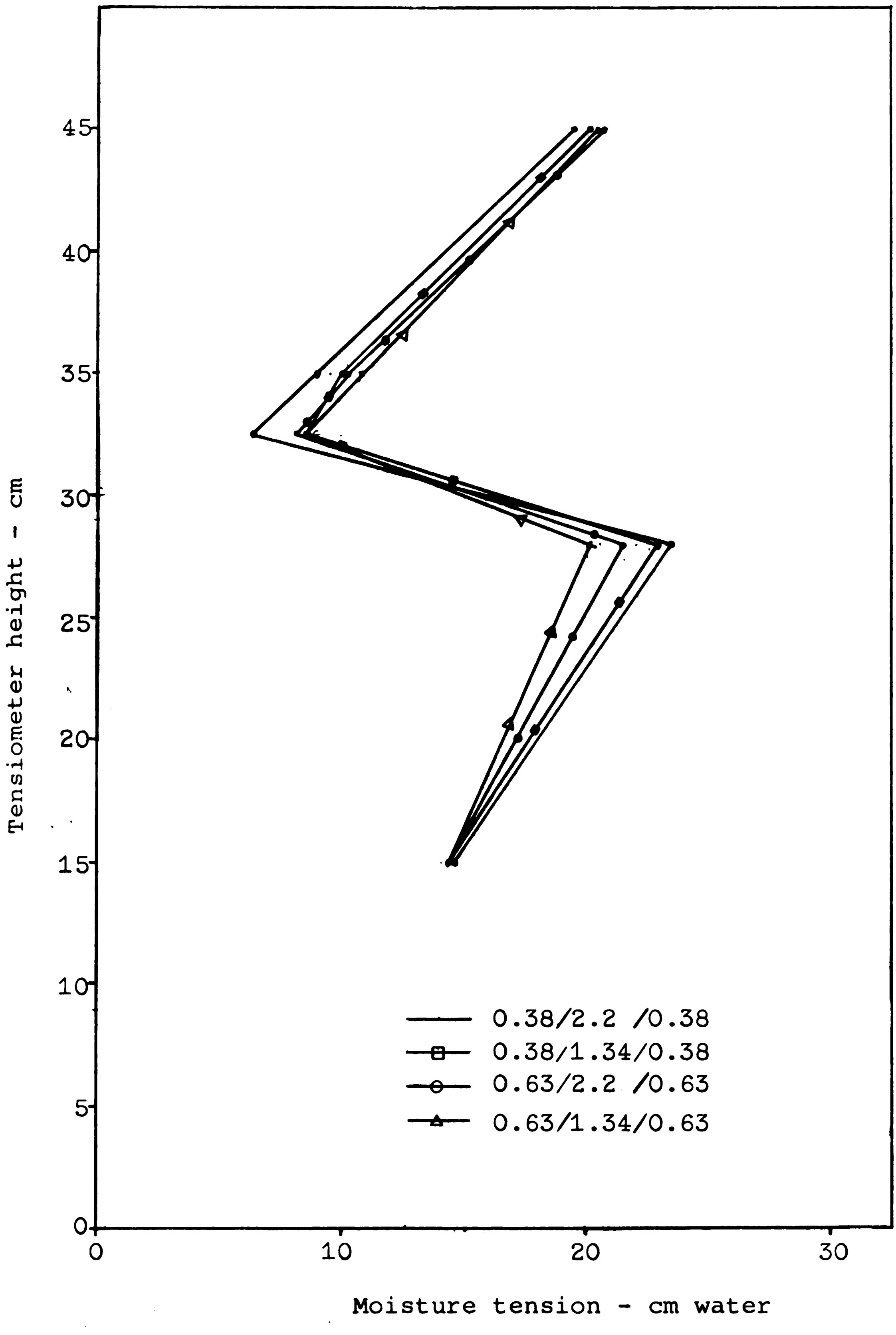


Figure 10. Effect of particle size of middle coarse layer on moisture tension profiles of 3 - layered sand columns of different body texture under static conditions.

Table 10 and figure 11 show the relation between moisture tension distribution in very fine sand columns as affected by 4 cm layers of three different coarse textured sands. Visual observation of the columns showed that the bottom layer of the three columns was wet, because capillarity was active up to the coarse stratum where the break occurred. Furthermore, an intermixing of the fine sand above with the coarse stratum to a depth of about 1 cm was also observed visually. The data (table 10) show a decrease in the effect of the stratum as its average particle size was decreased. Despite the intermixing of fine and coarse sand at the boundary, the discontinuity in the columns occurred. This was because only about 1 cm mixed layer and 2 cm or more of the unmixed coarse stratum remained to act as a barrier. The presence of the mixed layer makes the change in the moisture tension distribution gradual rather than abrupt and the mixed layer acts as a transition layer between the unmixed coarse stratum and the fine sand. Moisture tension in the mixed layer was not measured to verify this conclusion but it appears logical that the characteristic of the mixed layer should have average properties of the coarse and fine separates (37).

Moisture tension distribution in uniform sand columns, 2-layered sand column where the fine layer was over a coarse layer and 3-layered sand columns where a fine column was divided by a 4 cm coarse layer are plotted in figures

Table 10. The effect of particle size of the interposed coarse stratum on moisture tension distribution in 3-layered sand columns of the same body texture under static conditions.

Tensiometer height from bottom - cm	Average particle size of columns - mm dia		
	0.17 / 0.38 / 0.17	0.17 / 0.63 / 0.17	0.17 / 0.8 / 0.17
	Moisture tension - cm water		
45	32.9	30.5	29.7
35	20.0	17.9	17.1
32.5	19.7	18.6	18.2
25	24.0	24.0	24.0

[1]Average particle size of top layer / Average particle size of the interposed stratum / Average particle size of bottom layer.

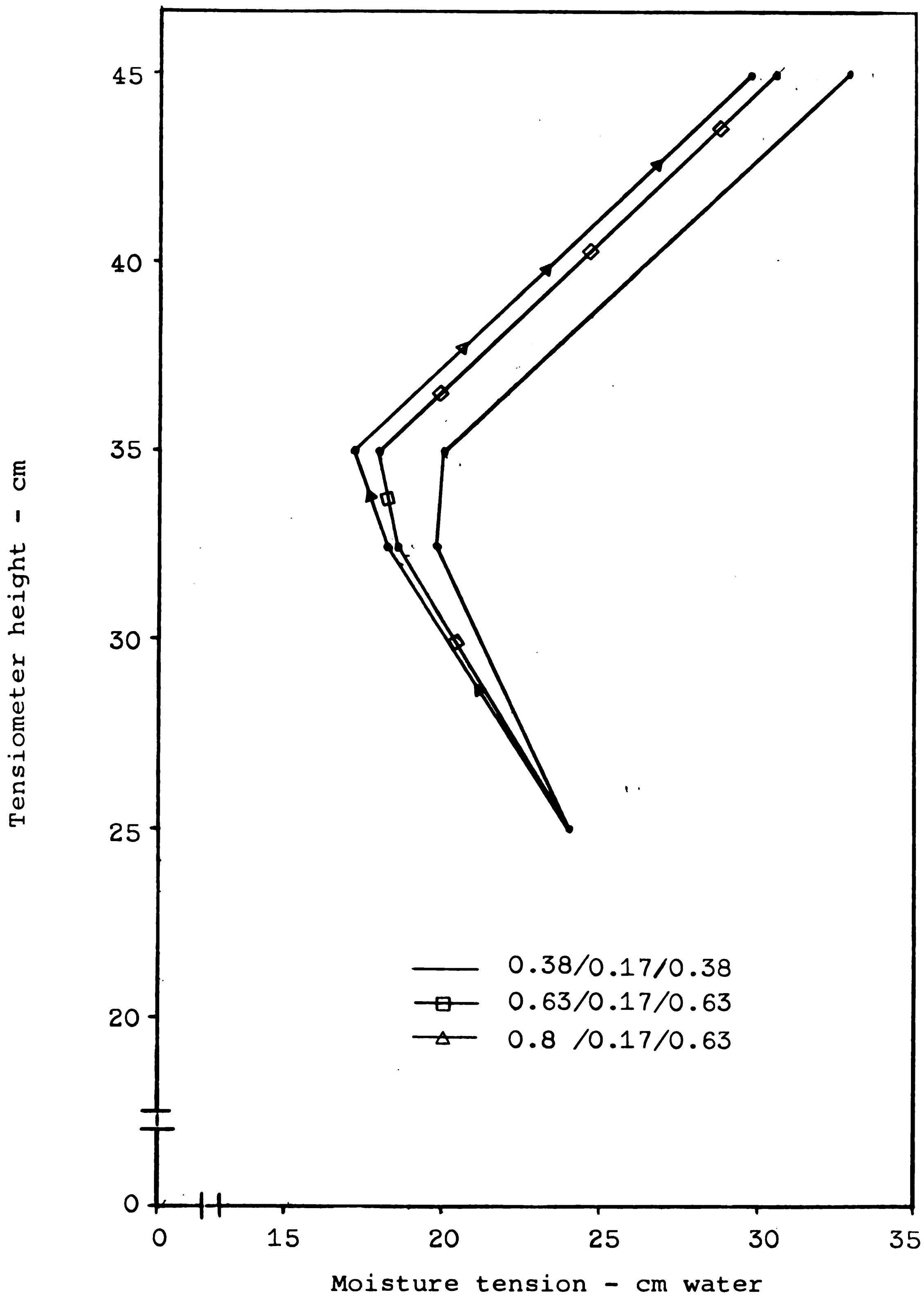


Figure 11. Moisture tension profiles of stratified sand columns as related to varying particle size of middle stratum under static conditions.

12, 13 and 14. Comparing the distributions of moisture tension of 2-layered columns with the uniform columns, the data shows a slight decrease in moisture tension in coarse bottom layers as compared with the same coarse sand in uniform sand columns. Meanwhile, the moisture tension in the upper fine layer was decreased greatly, in comparison to the fine uniform column at the same height.

Comparing moisture tension distribution of 3-layered columns with uniform columns, the moisture tension in the bottom layer increased slightly more than the uniform fine columns, while the moisture tension at the upper fine layer above the coarse stratum was decreased to a greater extent compared to the upper fine portion of 2-layered column and uniform fine column at the same height. The magnitude of the decrease in moisture tension in the fine layer above the coarse layer varied with the particle size of the layers.

The significant observation from these data is the similarity in the slopes of the moisture tension distribution in layered and uniform columns. The slopes of the 2-layered and 3-layered columns above the coarse layer are parallel, and the differences between the two are equal to the thickness of the coarse stratum in the 3-layered column.

As in the case of the uniform sand column if the moisture tension values are extrapolated to a zero height, the values obtained give a 1/1 slope for the fine bottom layer of the 3-layered sand column, and intersect a 1/1

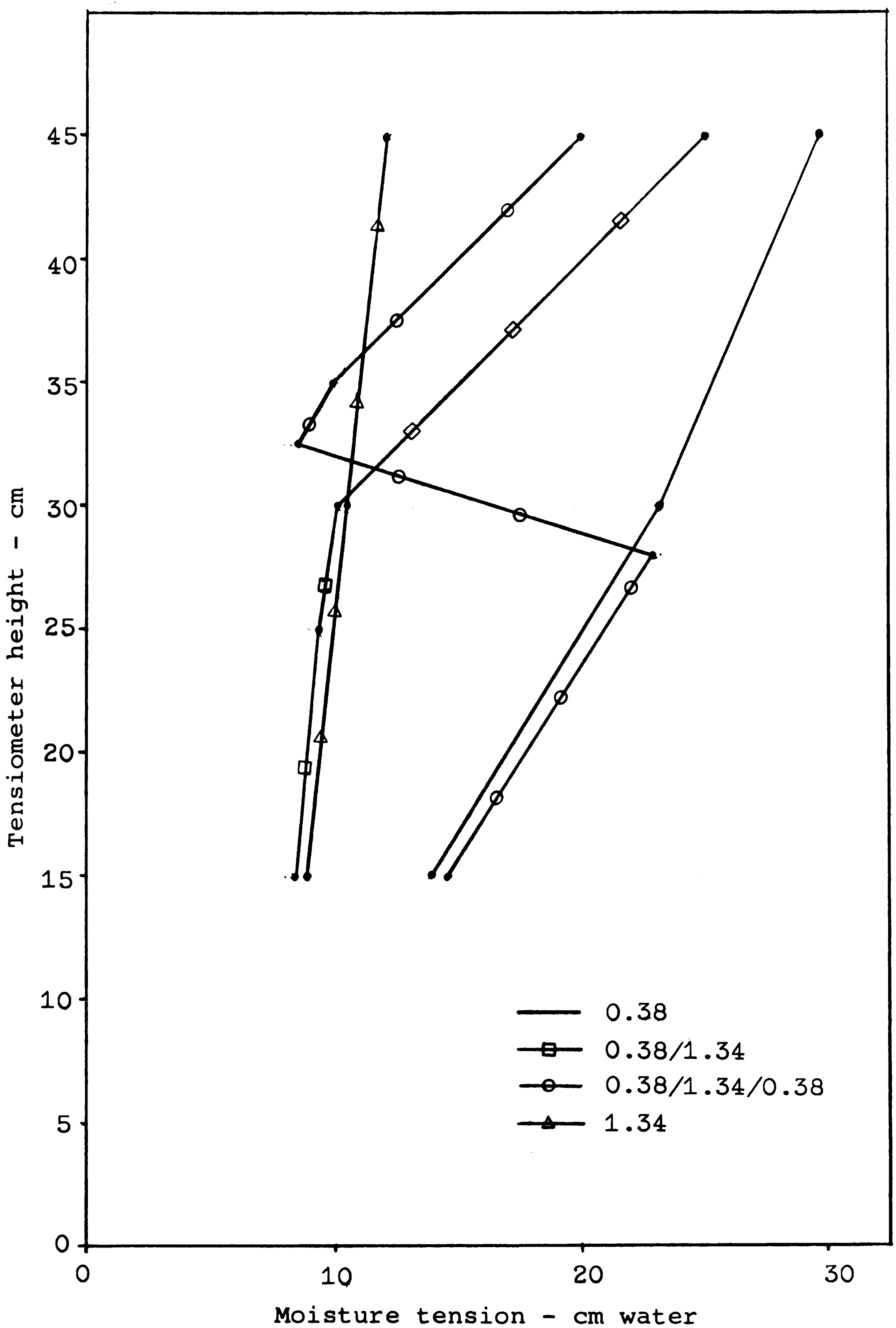


Figure 12. Moisture tension profiles of uniform, 2-layered and 3-layered sand columns (0.38, 1.34, 0.38/1.34 and 0.38/1.34/0.38 mm dia respectively) under static conditions.

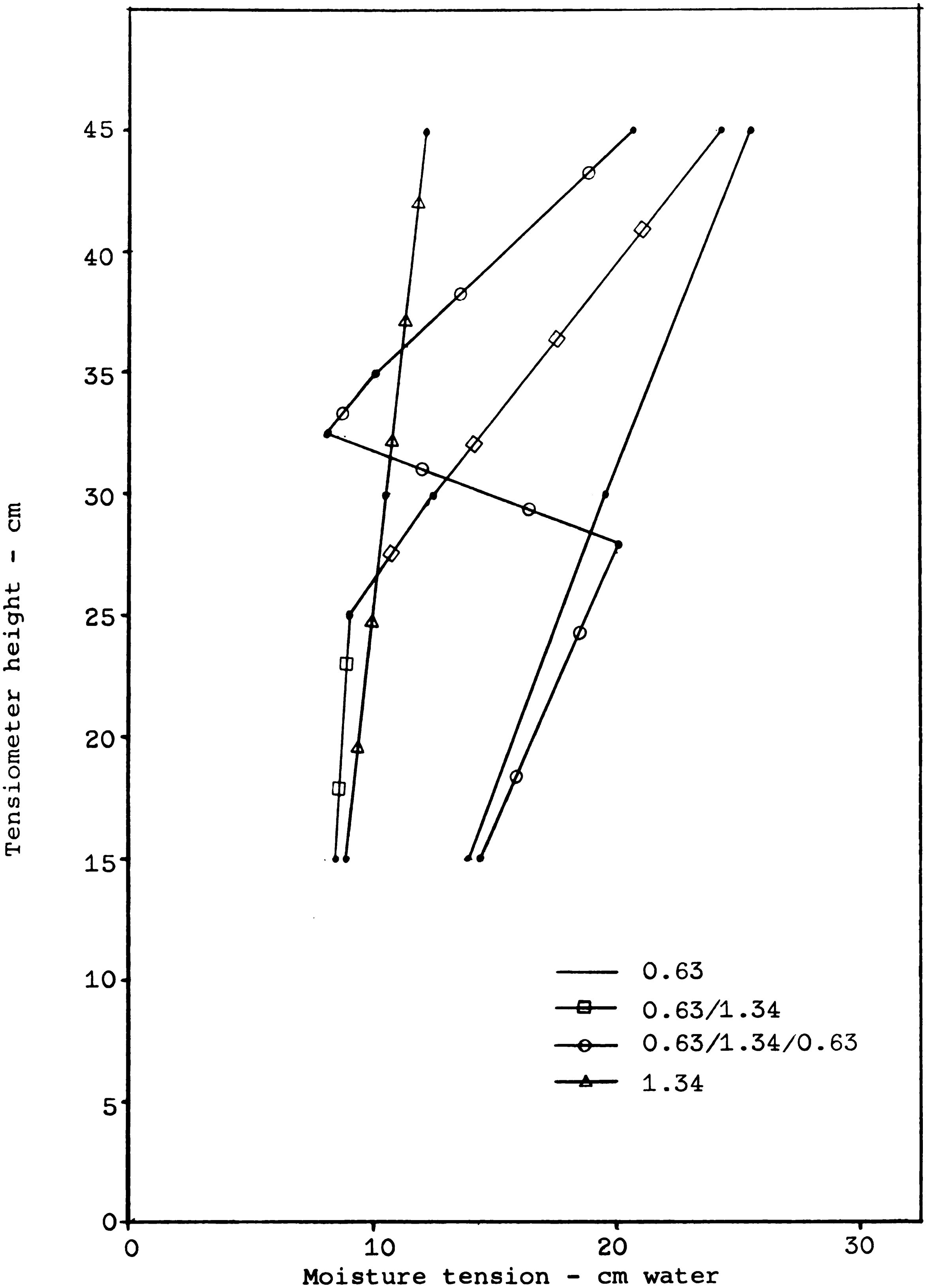


Figure 13. Moisture tension profiles of uniform, 2-layered and 3-layered sand columns (0.63, 1.34, 0.63/1.34 and 0.63/1.34/0.63 mm dia respectively) under static conditions.

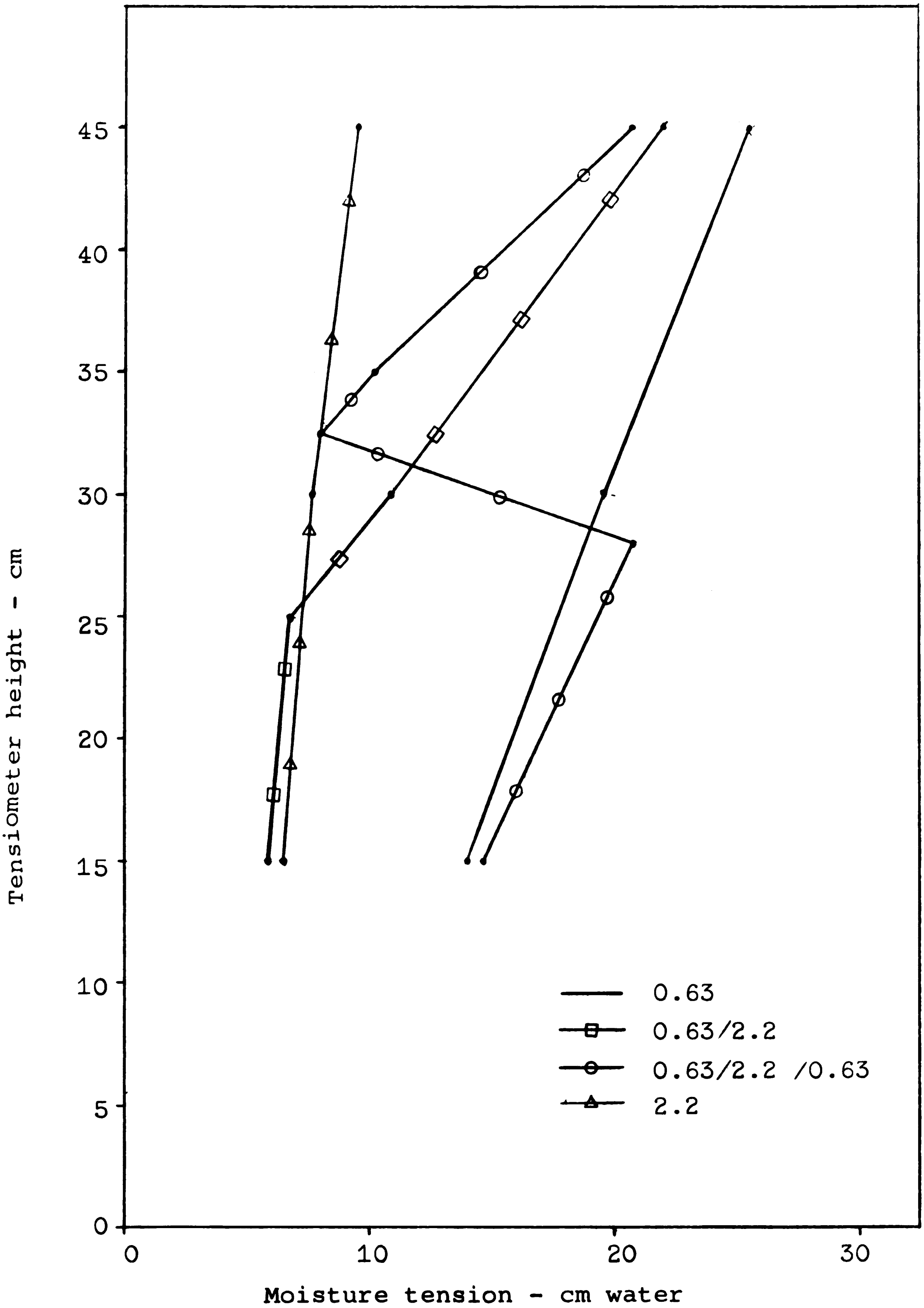


Figure 14. Moisture tension profiles of uniform, 2-layered and 3-layered sand columns (0.63, 2.2, 0.63/2.2 and 0.63/2.2/0.63 mm dia respectively) under static conditions.

slope at certain values similar to the height of the capillary rise for the coarse bottom layer of the 2-layered columns.

2. Pressure transducer technique

Due to failure of the water manometer type tensiometer to establish equilibrium with soil rapidly enough and difficulty arising from the exchange of water between the sample and the tensiometer, a pressure transducer tensiometer was used in these experiments.

a. Moisture tension distribution in uniform sand column

A uniform column 12 cm in diameter and 57 cm long with tensiometers at heights of 15, 24, 27, 30, 35, and 45 cm height from the bottom was prepared of the sand separate 0.72 mm dia. Moisture tension measurements were made after the column was drained and assumed to be at equilibrium. Water was added at three rates of application (15, 1, and 0.1 cc/min), and the moisture tensions were measured during the period of infiltration.

The results of the experiments are shown in table 11 and figure 15. Initial moisture tension distribution in the column shows a uniform gradual decrease in moisture tension from the surface to the bottom of the column. During the moisture flow in the column, with all rates of application, the data indicate that, at the wetting depths studied, the

Table 11. Moisture tension distribution in a uniform sand column of 0.72 mm dia under 3 - rates of water application.

Tensiometer height in the column - cm	Rate of water application - cc / min 15	1	0.1
	Moisture tension - cm water at initial static condition		
45	20.4	21.0	----
35	17.0	17.3	----
30	16.2	16.5	----
27	16.1	15.9	----
24	15.3	15.5	----
15	10.1	10.2	----
	Moisture tension - cm water at steady state condition		
45	7.9	9.4	11.3
35	6.4	8.5	11.2
30	6.4	8.4	11.2
27	6.4	8.4	11.2
24	6.4	8.4	11.2
15	6.4	8.6	9.7
	Moisture tension - cm water at final static condition		
45	21.0	----	21.7
35	17.3	----	18.0
30	16.5	----	17.0
27	15.9	----	16.3
24	15.5	----	15.8
15	10.2	----	10.1

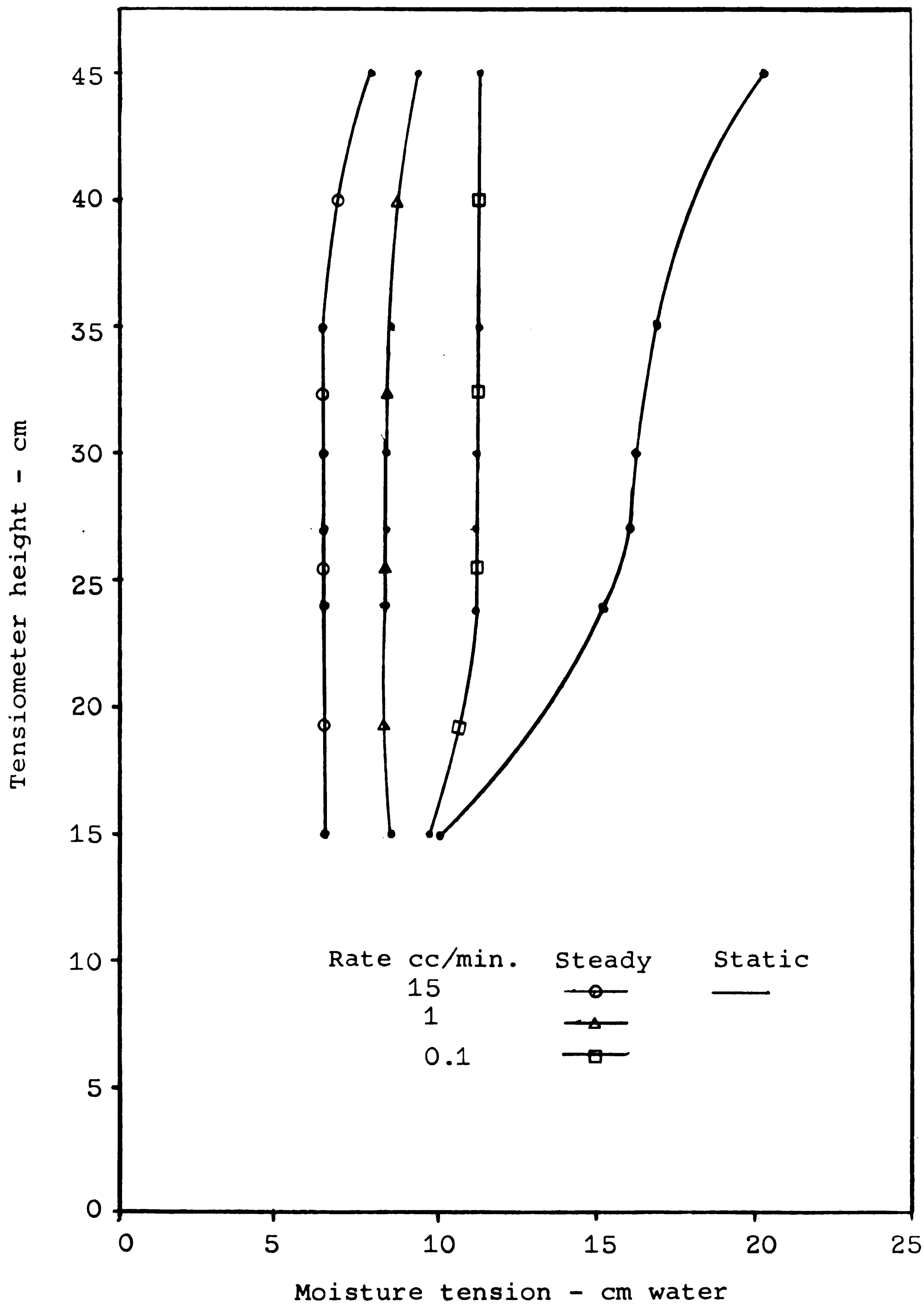


Figure 15. Moisture tension profiles of a uniform sand column of 0.72 mm dia under 3-rates of water application.

moisture tensions throughout the column approached constant values. The lower rates of water application produced higher moisture tensions (39,40). The steady state values of moisture tension were persistant during the infiltration after the tensions reached the constant value for the particular rate.

The period of time required for each tensiometer to reach constant readings after passage of the wetting front was different for each rate of water application. The moisture tensions decreased and reached the steady state values and free water flow from the outlet occurred in less than 30 min with the highest rate of water application. At 1 cc/min, the time required for the tensiometers to change and reach steady state increased to 4-5 hr. No appreciable amount of water was retained in the sand column as 95 to 97% of water added was recovered at the end of the experiment.

b. moisture tension distribution in 3-layered sand columns

The results of the experiments with water manometers showed that the presence of a coarse textured layer does strongly influence the moisture tension distribution in stratified sand columns. On the basis of these results it was decided that further studies should be carried on to study moisture tension distribution in relation to:

(1) Variation in the texture of the middle stratum ranging from particle sizes greater than particles in the

upper and lower layers to materials finer in particles than in the upper and lower layers.

(2) Variation in rate of water application from a high to low rate of application.

(3) The minimum thickness of an interposed stratum needed to cause a discontinuity.

Six sand columns of the same sand which was used in the previous uniform column (0.72 mm dia) were prepared with 1 cm thick strata of sand of a different particle size in the center of the 57 cm columns as listed in table 12.

Moisture tension in the columns were measured at 15, 27, 30, 35, and 45 cm from the bottom of the column.

At the beginning of the experiment uniform water application was begun and the top tensiometer was opened to the pressure transducer and changes in moisture tension were used to follow the movement of the water front with time. Frequent readings of all tensiometers were recorded until the moisture tensions throughout the column came to a steady state. Water application was stopped and the columns allowed to drain. The volume of water added and recovered was measured.

Different rates of water application were used with each column as shown in table 12.

When water application was discontinued with each column, samples were taken from around the tensiometers and moisture content was determined.

Table 12. Description of the sand columns and rate of water application studied.

Column No.	Avg. particle size[1] of column - mm dia	Rate of water application - cc/min						
		60	15	1	0.5	0.1	0.05	0.025
1	0.72 / 1.55 / 0.72	X	X	X	X			
2	0.72 / 1.3 / 0.72	X	X	X	X			
3	0.72 / 1.1 / 0.72	X	X	X	X			
4	0.72 / 0.92 / 0.72		X	X		X	X	X
5	0.72 / 0.46 / 0.72		X	X		X		
6	0.72 / 0.37 / 0.72		X	X		X	X	X

[1] Average particle size of the top layer / Average particle size of the interposed stratum / Average particle size of the bottom layer.

In order to simplify presentation of the results the effect of the particle size of the interposed stratum under one constant rate of water application (15 cc/min) are presented first and then those varying in rate of watter application under one constant particle size of the interposed stratum (0.72 / 1.55 / 0.72).

The results of these experiments are plotted as moisture tension versus time for each tensiometer. The moisture tension at initial static and at steady state conditions were plotted versus height of each tensiometer.

(1). Particle size of the middle stratum

The data in table 13 and figures 16 through 21 show effect of particle size of the stratum at one water application rate. The moisture tension in every column decreased from the surface of the column down to where it approached its lowest reading above the stratum. The moisture tension increased in the fine layer immediately below the intervening stratum then decreased again to the bottom of the column. The moisture tension distribution showed a complete discontinuity with 1.55 mm particle size in the stratum (figure 16) and decreased in discontinuity when the particle size of the column approached uniformity. The moisture tension discontinuity became evident again when the particle size of the stratum became finer than the particle size of the main column. The discontinuity was complete only with the coarsest stratum where there was no change in the

Table 13. Moisture tension distribution in 3-layered sand columns with middle layers of different particle size, but a constant (15 cc/min) rate of water application.

Tensiometer Height in the column - cm	Average particle size of layered columns - mm dia					
	0.72 / 1.55 / 0.72	0.72 / 1.3 / 0.72	0.72 / 1.1 / 0.72	0.72 / 0.92 / 0.72	0.72 / 0.46 / 0.72	0.72 / 0.37 / 0.72
	Moisture tension-cm water at Initial Static condition					
45	20.8	22.6	23.1	23.9	22.8	22.6
35	11.2	13.2	13.7	15.2	15.5	15.1
30	6.3	8.0	8.7	10.9	12.2	11.8
27	16.8	15.4	13.6	13.0	12.8	13.6
15	9.9	10.3	10.6	10.6	10.5	10.0
	Moisture tension-cm water at steady state condition					
45	5.7	8.0	8.9	10.1	10.2	7.9
35	2.5	6.3	6.7	7.1	6.4	4.8
30	-1.9	2.7	3.2	5.6	5.7	3.8
27	2.9	5.7	5.8	6.7	5.8	4.2
15	2.3	7.3	8.6	8.7	6.8	5.8
	Moisture tension-cm water at Final Static condition					
45	21.5	22.8	23.0	24.1	23.1	22.8
35	11.9	14.3	14.8	15.7	15.8	14.9
30	6.9	9.3	9.8	11.2	12.7	11.7
27	17.3	16.6	14.5	13.9	13.4	13.5
15	10.6	10.8	11.0	10.5	10.3	10.5

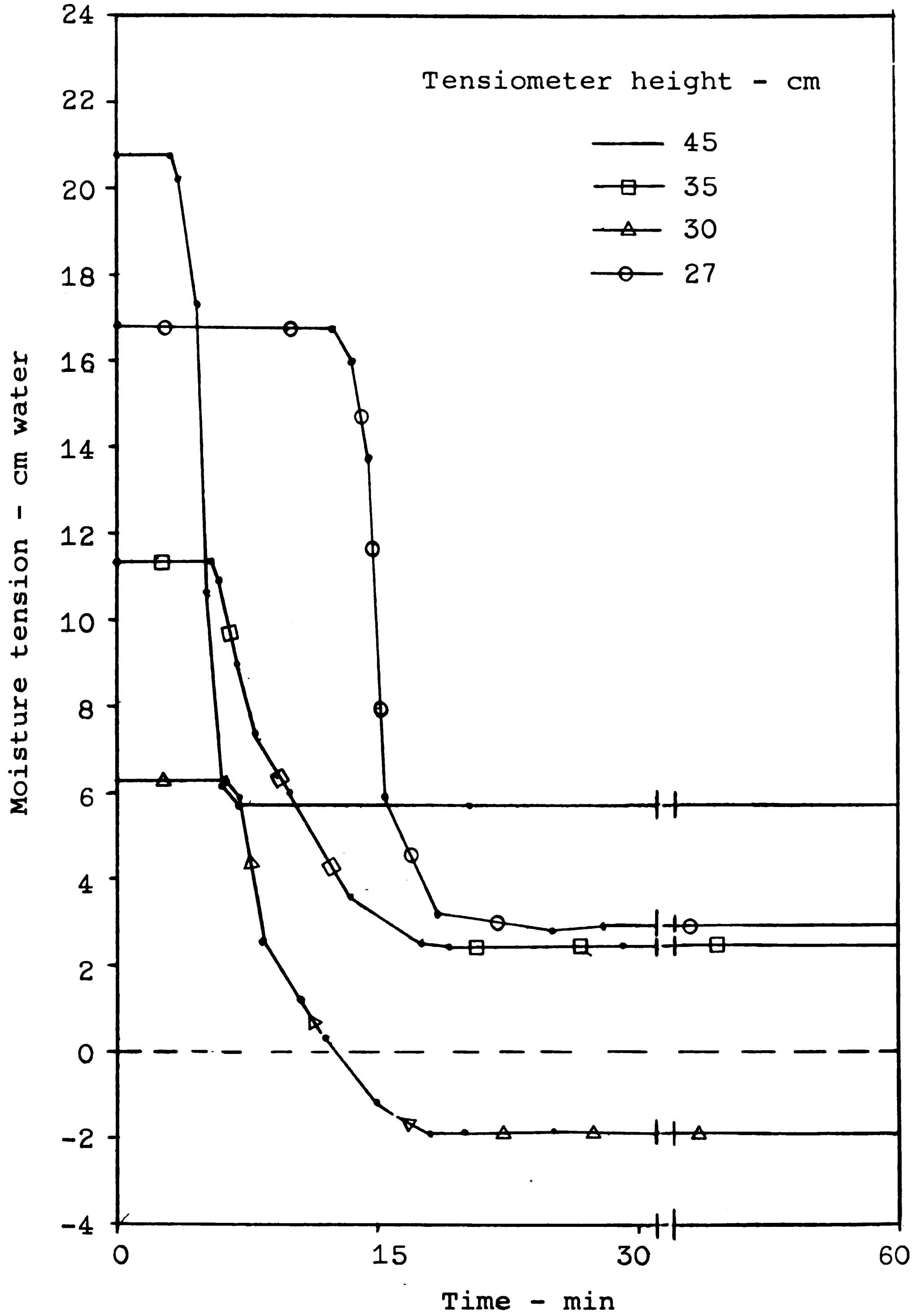


Figure 16. Changes in moisture tension with time in a 3-layered sand column (0.72/1.55/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 15cc/min.

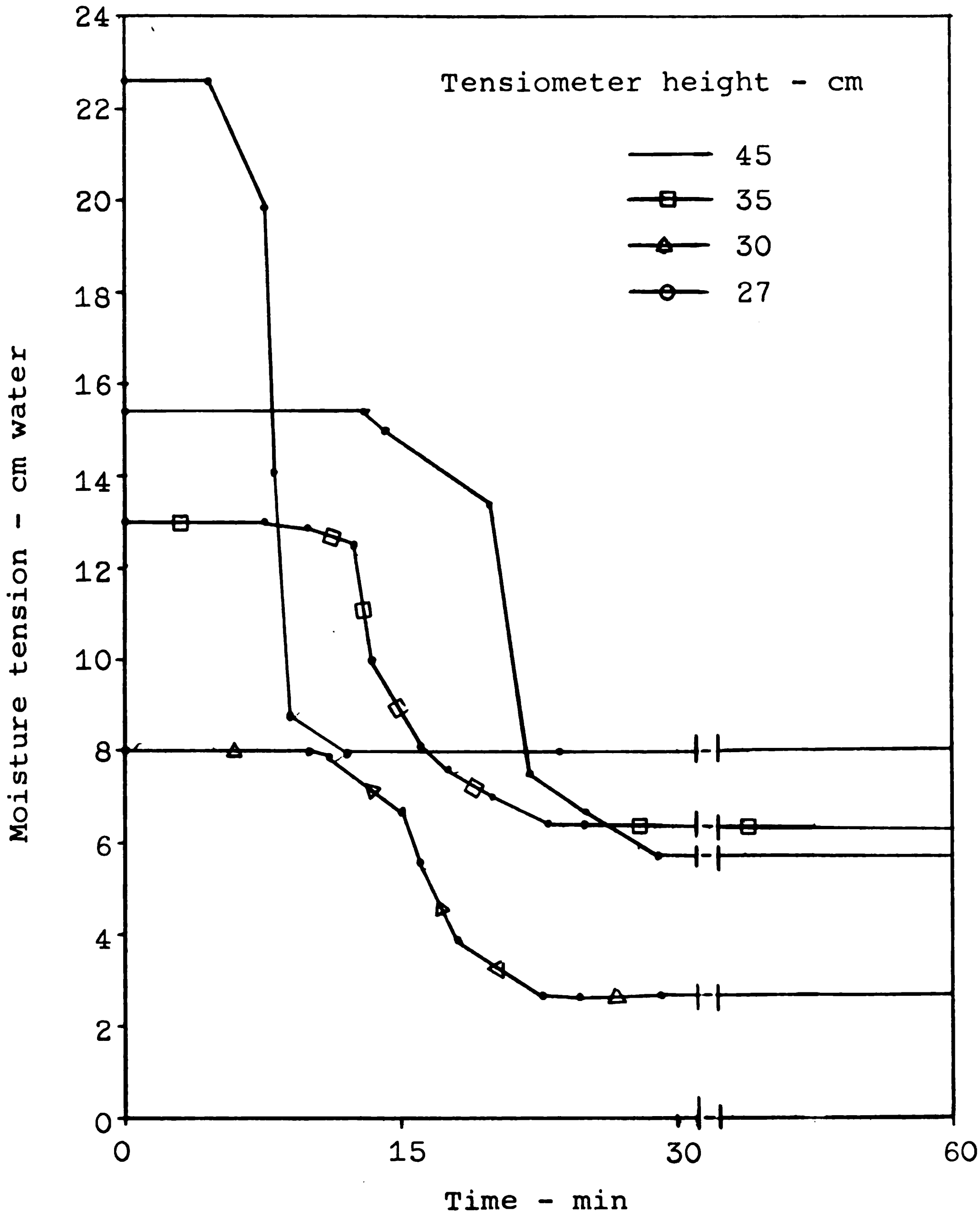


Figure 17. Changes in moisture tension with time in a 3-layered sand column (0.72/1.3/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 15 cc/min.

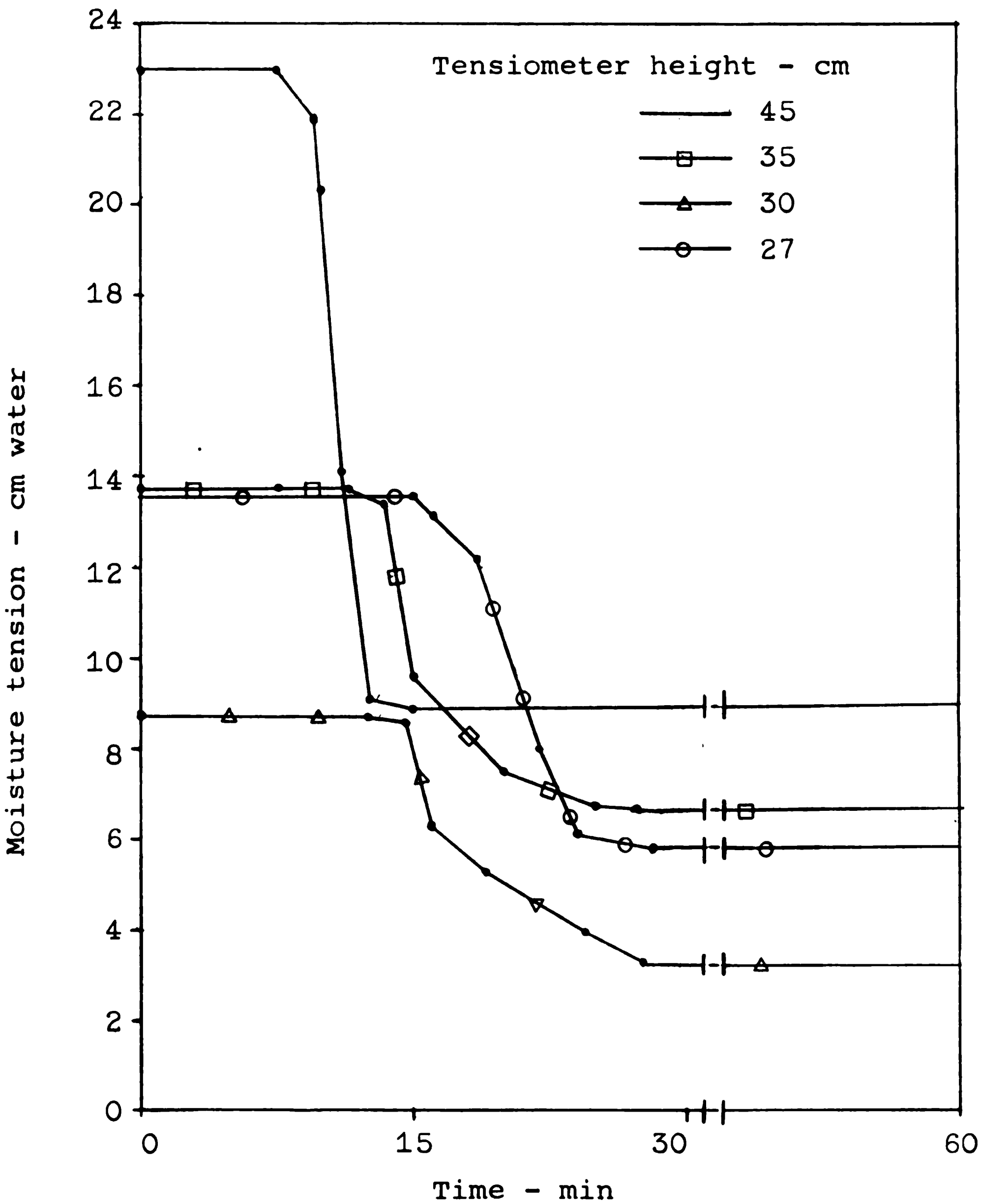


Figure 18. Changes in moisture tension with time in a 3-layered sand column (0.72/1.1/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 15 cc/min.

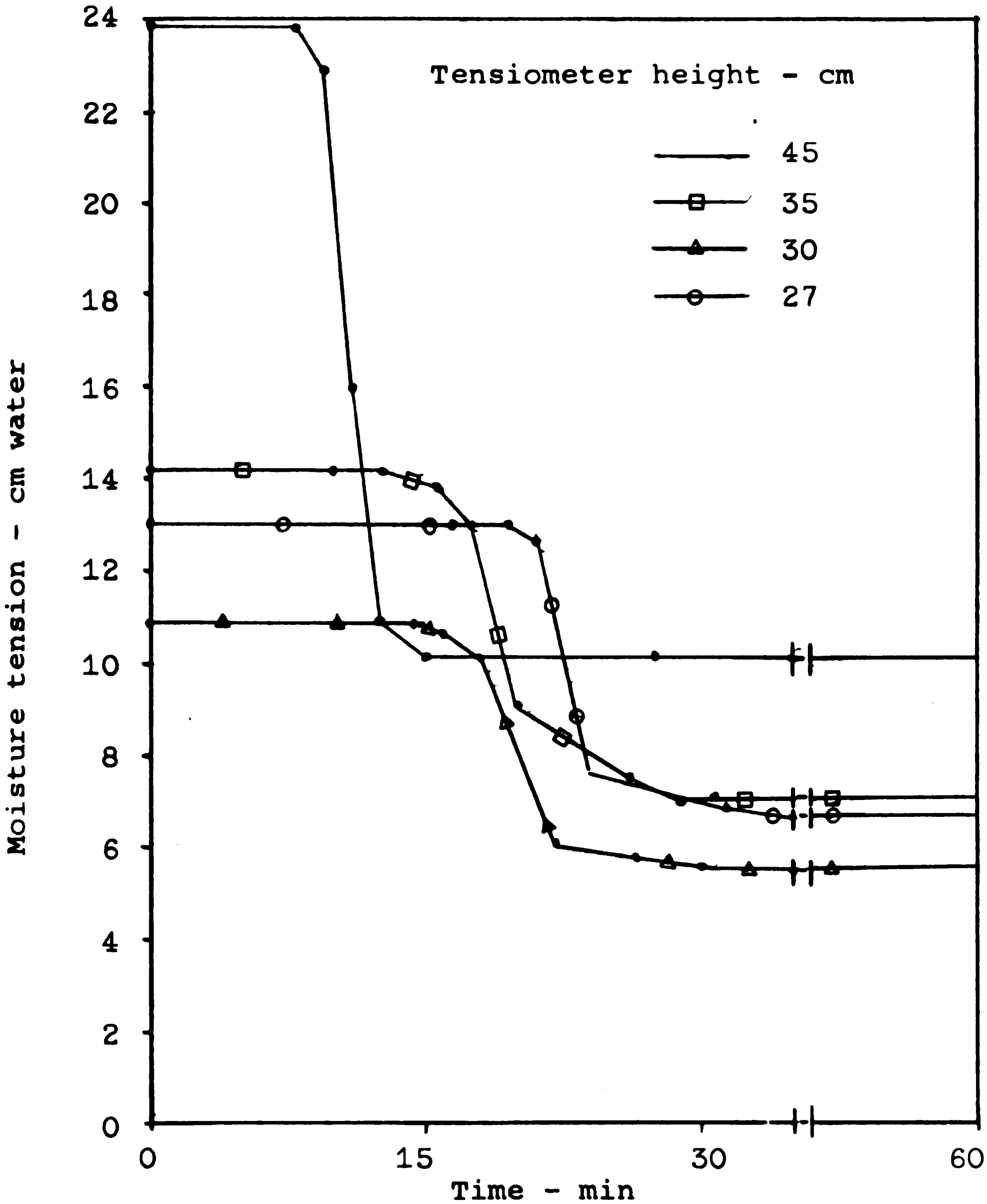


Figure 19. Changes in moisture tension with time in a 3-layered sand column (0.72/0.92/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 15 cc/min.

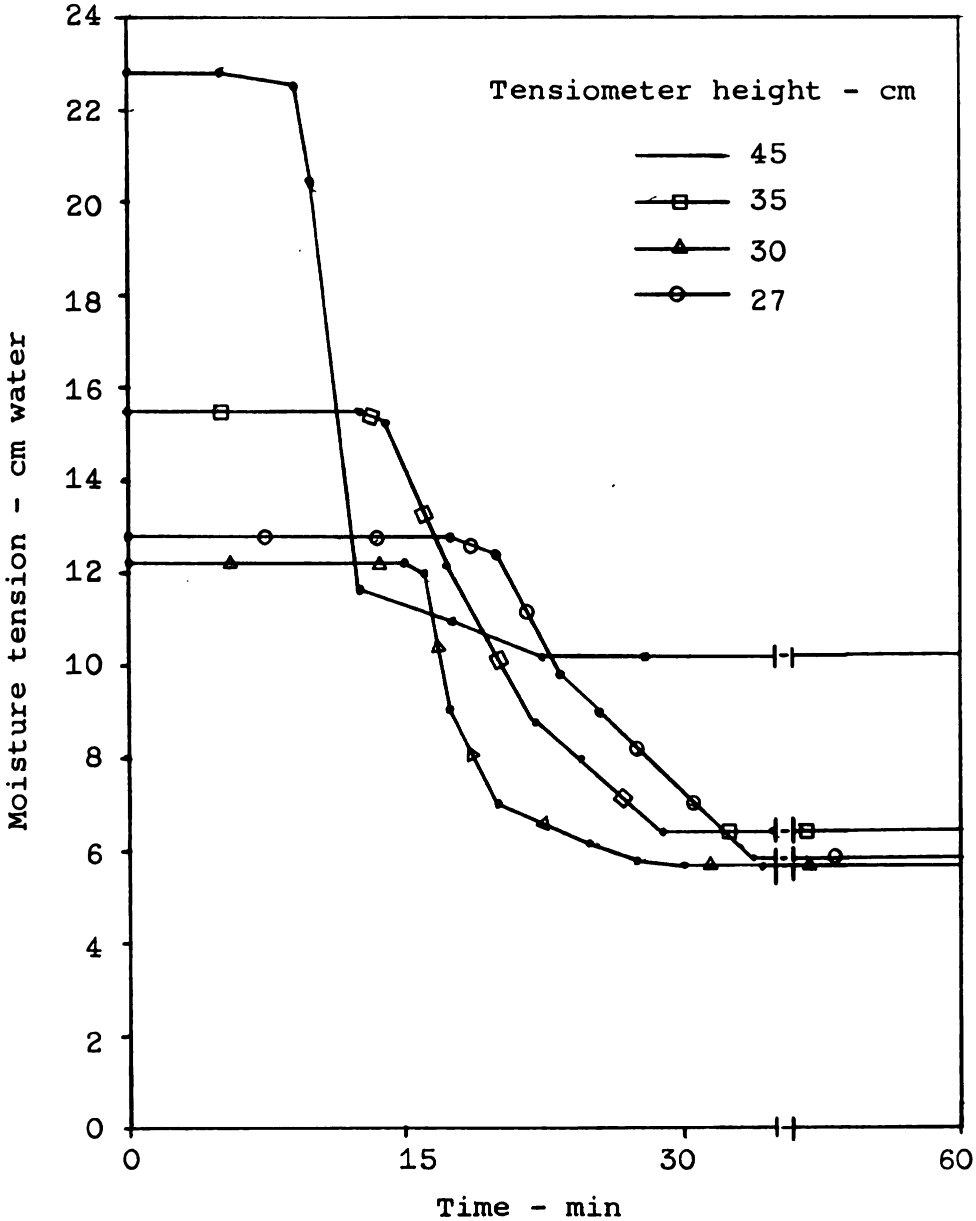


Figure 20. Changes in moisture tension with time in a 3-layered sand column (0.72/0.46/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 15 cc/min.

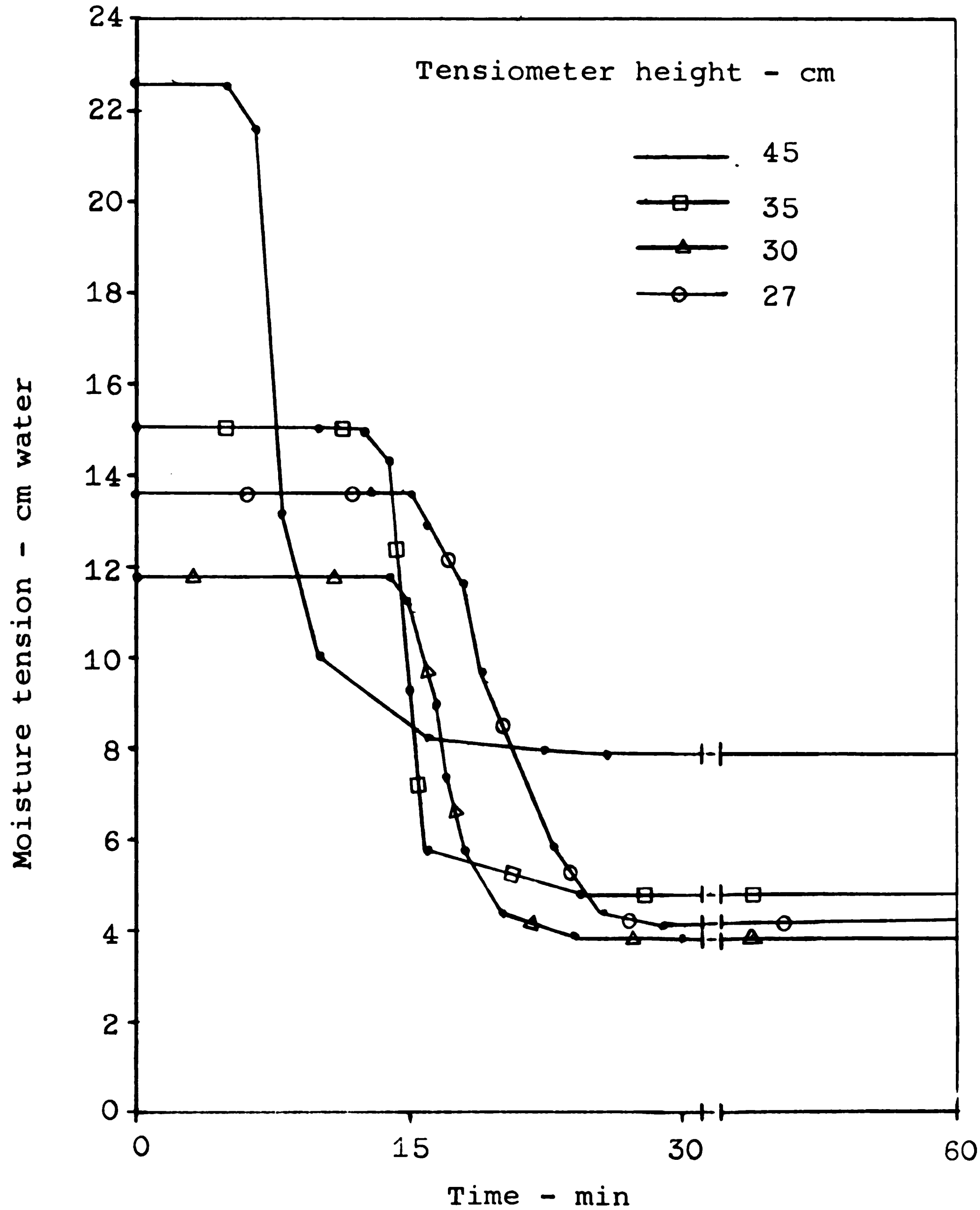


Figure 21. Changes in moisture tension with time in a 3-layered sand column (0.72/0.37/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 15 cc/min.

moisture tension below the coarse stratum until there was a zone of free water accumulation above the coarse stratum extending to about 4 cm which could be observed visually. Positive pressure reading of 1.9 cm occurred above the coarse layer before the tension below the layer dropped to its steady state value. This observation was further verified with the data of moisture content determination shown in (table 14 and figure 22). In general, the moisture content in the columns followed inversely the same trend of moisture tension distribution where the moisture content above the stratum decreased and then increased with change in particle size of the stratum from coarser to finer than the particle size of the main column. The moisture content above the stratum was highest with the coarsest stratum.

(2) Rate of water application

Distribution of moisture tension in stratified columns was also studied under rates of water application. These are listed in table 12. The results of the experiments are presented in tables 15 through 20 and figures 23 through 34.

Moisture tension of the columns was affected by the rate of water application. The moisture tension at different depths of the columns was decreased with increase in time of water application, and approached steady state values. These values remained unchanged with further water application unless the rate of water application

Table 14. Distribution of moisture in 3 - layered sand columns as related to varying particle size in the middle layer (28 cm of 0.72 mm dia sand above and below).

Location of the samples - cm from bottom	Average particle size of the middle layer-mm dia						
	1.55[1]	1.55[2]	1.3	1.1	0.92	0.46	0.37
45	3.0	3.2	3.2	3.1	2.9	2.5	2.7
35	3.4	5.3	4.7	4.4	3.1	2.6	4.1
30	6.9	19.6	11.4	9.1	3.8	2.8	7.2
27	3.2	4.9	3.8	3.6	3.1	3.0	4.3

[1]Middle layer is 0.2 cm thick.

[2]Middle layer is 1 cm thick.

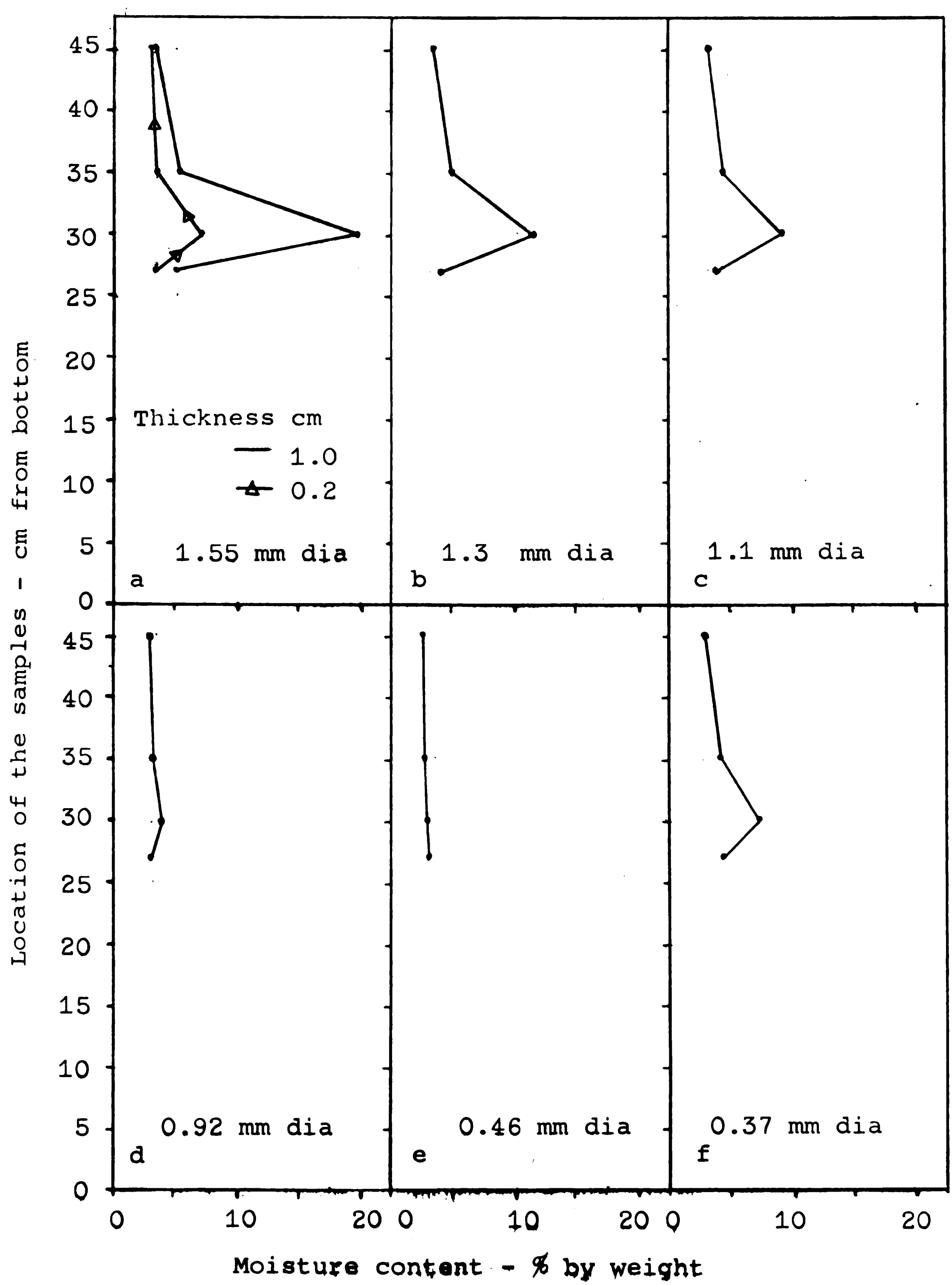


Figure 22. Moisture content profiles of stratified sand columns as related to particle size of middle stratum at the end of the experiment.

Table 15. Moisture tension distribution in a 3-layered sand column (0.72 / 1.55 / 0.72 mm dia, 28 + 1 + 28 cm) under 4-rates of water application.

Tensiometer height in the column - cm	Rate of water application-cc/min.			
	60	15	1	0.5
	Moisture tension cm water at initial static condition			
45	20.7	20.8	21.5	21.5
35	11.2	11.4	11.9	12.0
30	5.4	6.3	6.9	7.2
27	16.4	16.8	17.3	16.6
15	9.9	10.0	10.6	10.4
	Moisture tension-cm water at steady state condition			
45	4.6	5.7	10.3	11.0
35	2.0	2.5	6.6	8.2
30	-2.7	-1.9	3.0	3.5
27	0.2	2.9	6.9	8.7
15	-7.1	2.3	10.2	10.1
	Moisture tension-cm water at final static condition			
45	20.8	21.5	21.5	20.9
35	11.4	11.9	12.0	11.9
30	6.3	6.9	7.2	7.1
27	16.8	17.3	16.6	16.8
15	10.0	10.6	10.4	10.4

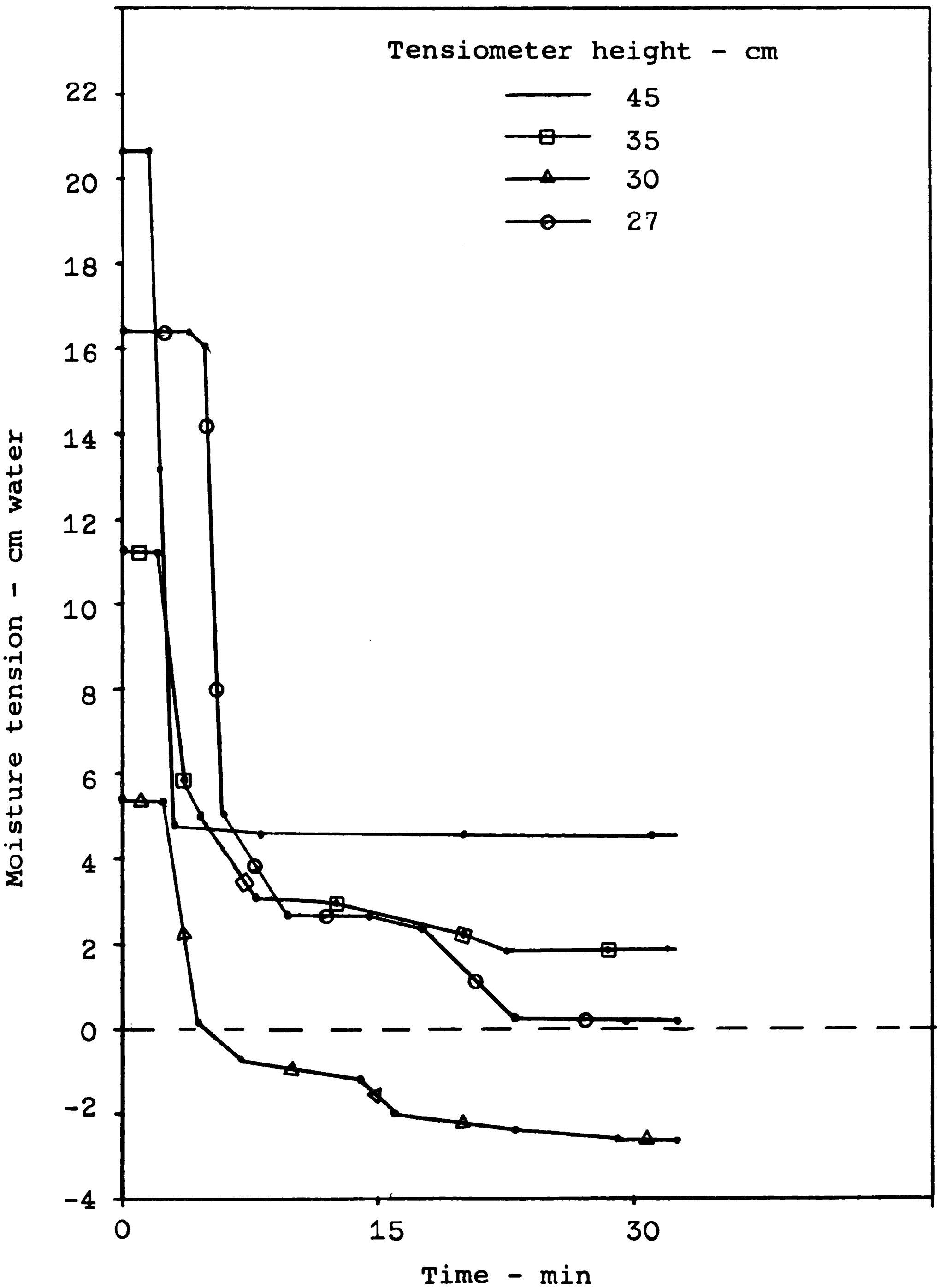


Figure 23. Changes in moisture tension with time in a 3-layered sand column (0.72/1.55/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 60 cc/min.

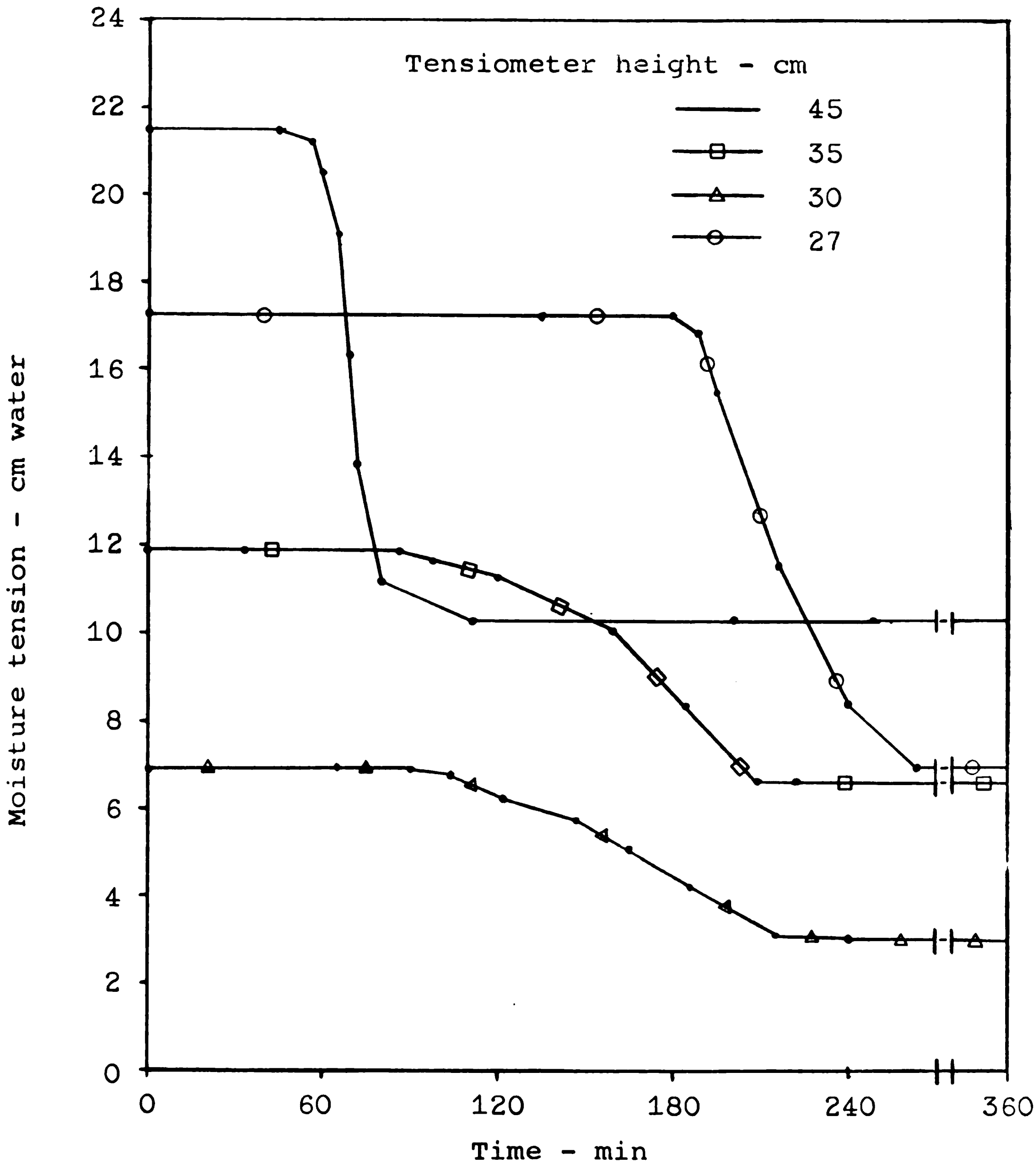


Figure 24. Changes in moisture tension with time in a 3-layered sand column (0.72/1.55/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 1 cc/min.

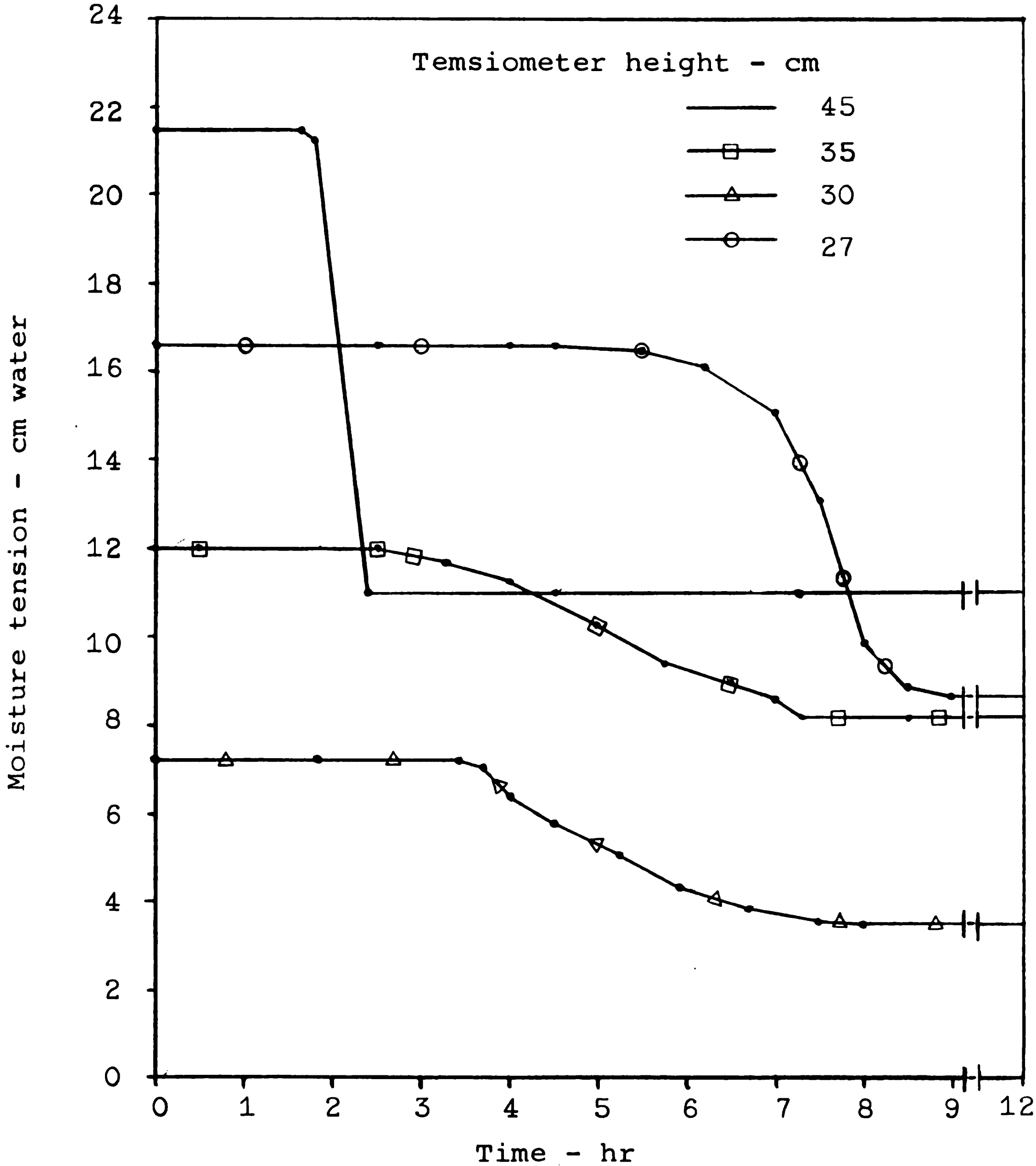


Figure 25. Changes in moisture tension with time in a 3-layered sand column (0.72/1.55/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 0.5 cc/min.

Table 16. Moisture tension distribution in a 3-layered sand column (0.72/1.30/0.72 mm dia, 28 + 1 + 28 cm) under 4-rates of water application.

Tensiometer height in the column - cm	Rate of water application-cc/min 60	15	1	0.5
	Moisture tension-cm water at initial static condition			
45	22.2	22.6	23.4	23.6
35	12.7	13.2	14.3	14.2
30	7.6	8.0	9.2	9.4
27	14.3	15.4	16.6	16.2
15	10.1	10.3	10.8	10.8
	Moisture tension-cm water at steady state condition			
45	6.5	8.0	10.7	11.0
35	5.0	6.3	9.0	9.6
30	2.4	2.7	5.0	5.2
27	4.2	5.7	8.1	9.1
15	-3.0	7.3	10.7	10.7
	Moisture tension-cm water at final static condition			
45	22.6	23.4	23.6	23.2
35	13.2	14.3	14.2	14.7
30	8.0	9.2	9.4	10.0
27	15.4	16.6	16.2	16.4
15	10.3	10.8	10.8	10.8

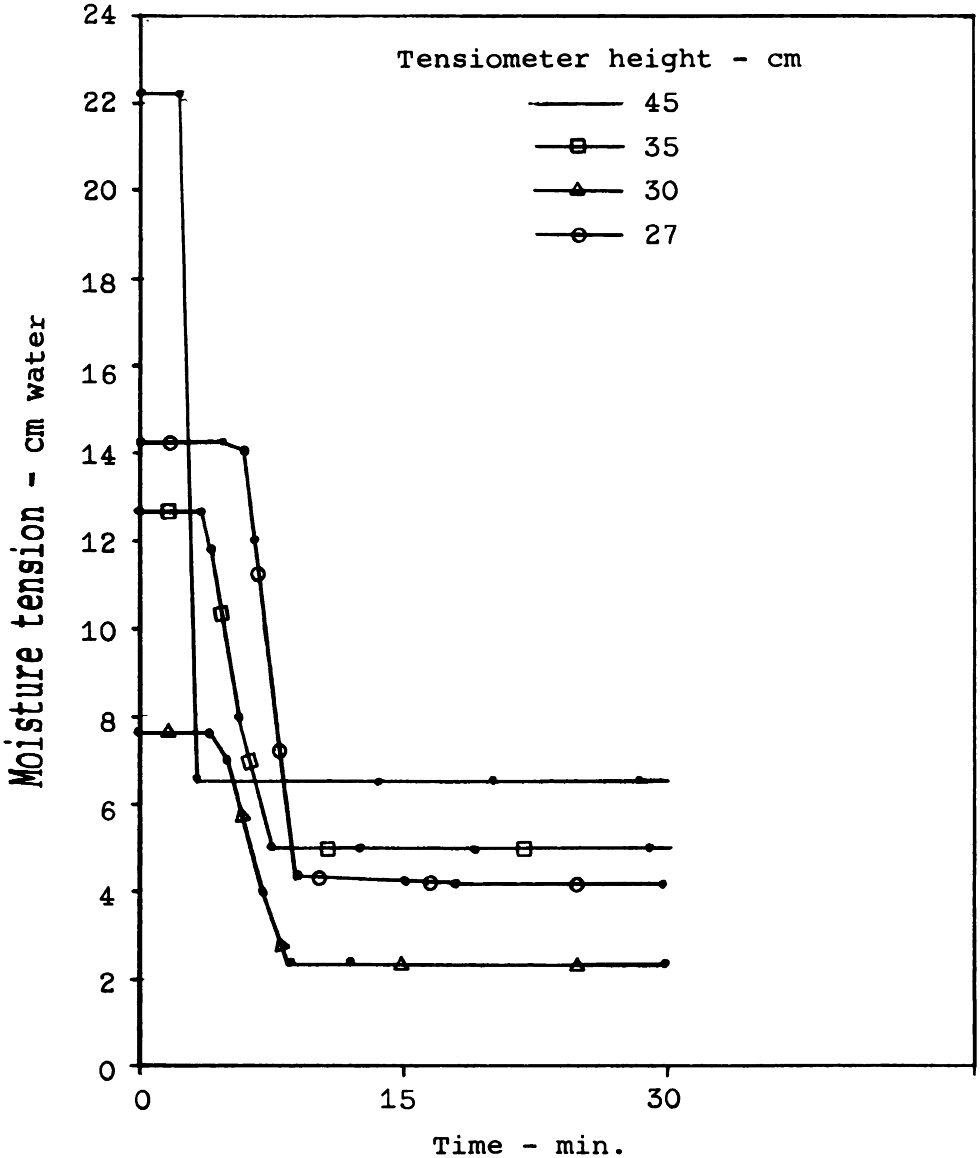


Figure 26. Changes in moisture tension with time in a 3-layered sand column (0.72/1.3/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 60 cc/min.

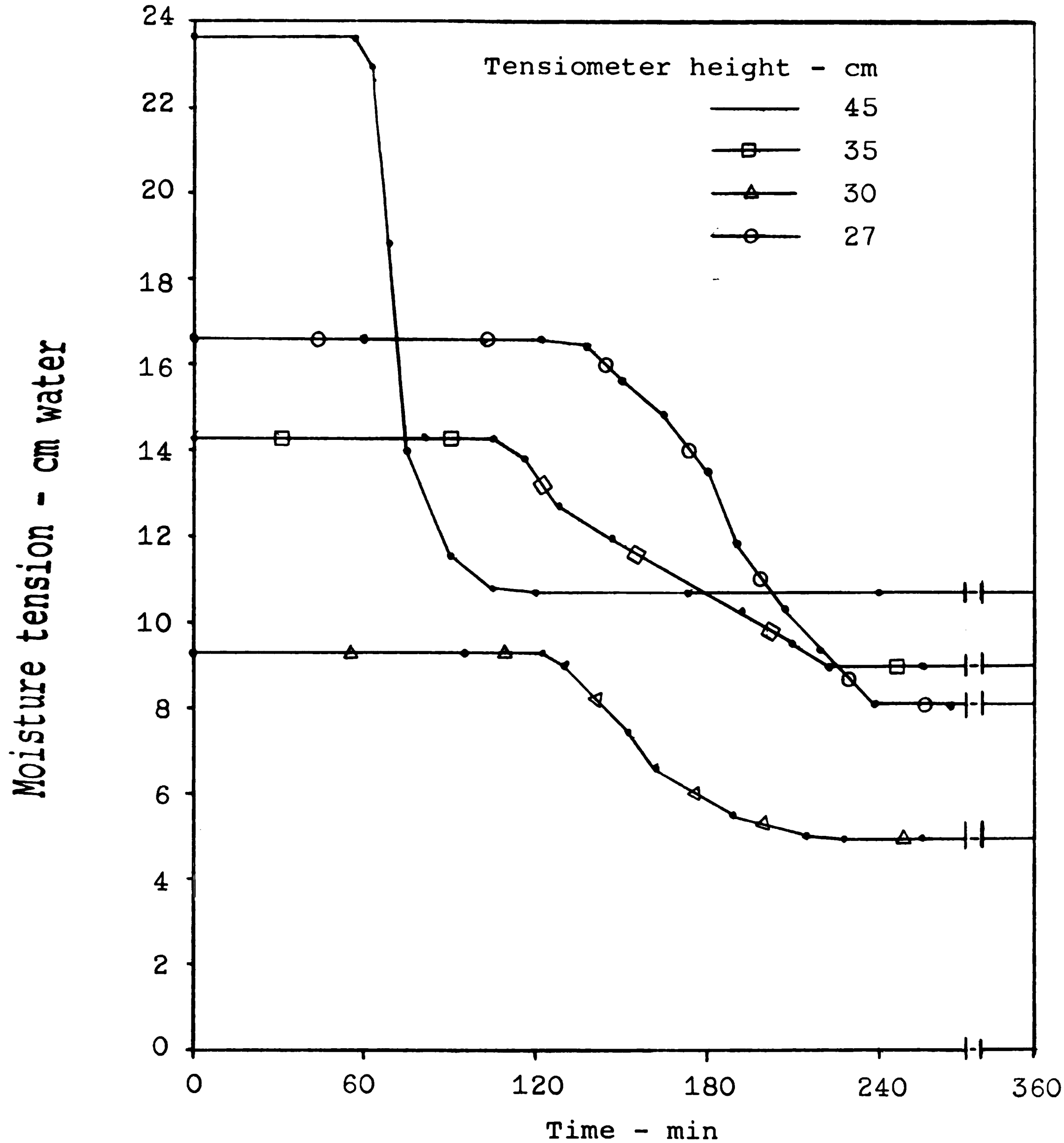


Figure 27. Changes in moisture tension with time in a 3-layered sand column (0.72/1.3/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 1 cc/min.

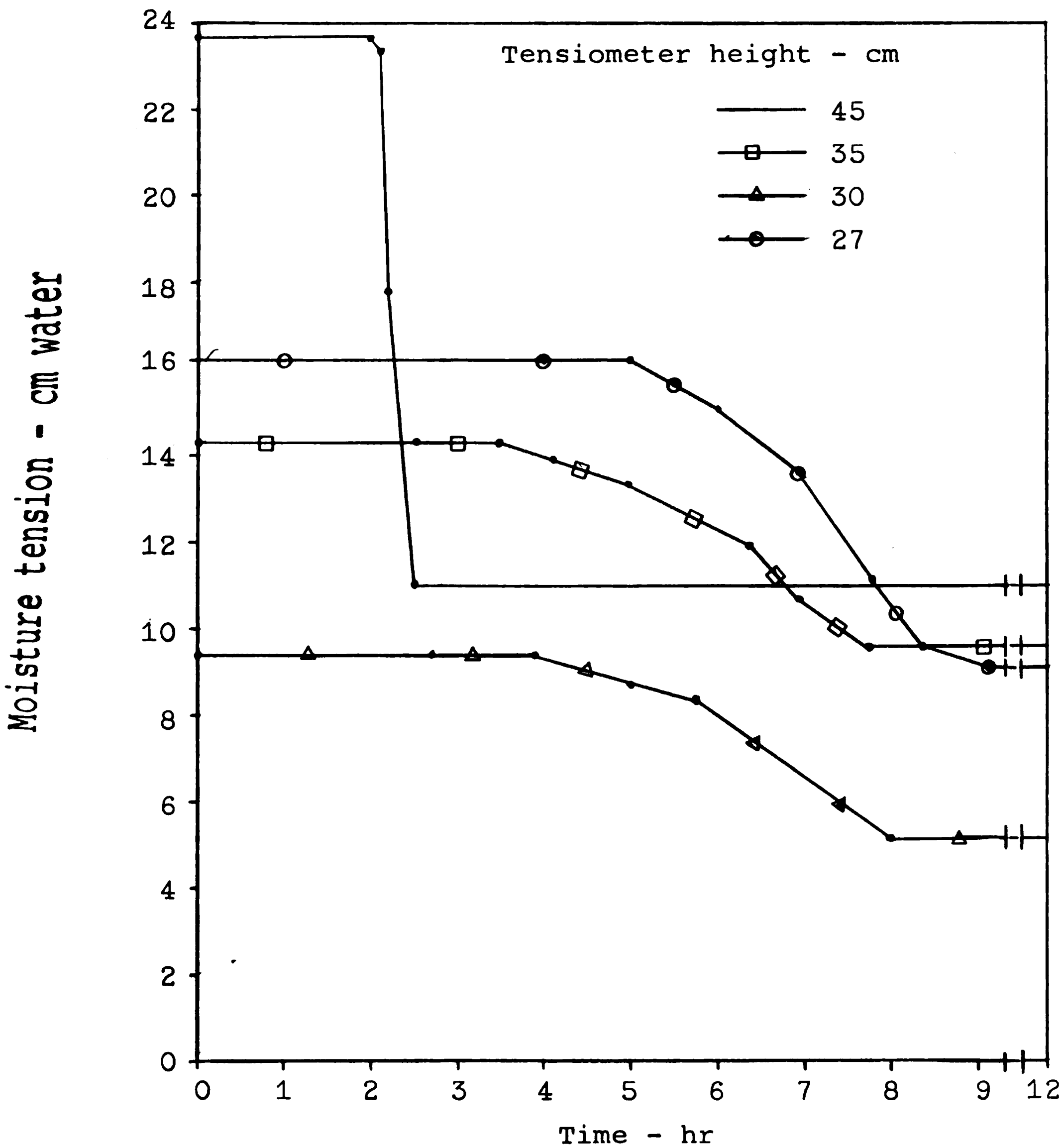


Figure 28. Changes in moisture tension with time in a 3-layered sand column (0.72/1.3/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 0.5 cc/min.

Table 17. Moisture tensions in a 3-layered sand column (0.72/1.1/0.72 mm dia, 28 + 1 + 28 cm) under 4-rates of water application.

Tensiometer height in the column - cm	Rate of water application-cc/min			
	60	15	1	0.5
	Moisture tension-cm water at initial static condition			
45	22.9	23.1	23.9	23.7
35	13.5	13.7	14.8	14.8
30	8.5	8.7	9.8	10.0
27	13.2	13.6	14.5	15.8
15	10.0	10.6	11.0	10.4
	Moisture tension-cm water at steady state condition			
45	7.6	8.9	10.6	11.2
35	5.2	6.7	9.4	10.3
30	2.7	3.2	5.1	5.4
27	5.0	5.8	8.0	9.3
15	4.1	8.6	10.7	10.4
	Moisture tension-cm water at final static condition			
45	23.1	23.9	23.7	24.0
35	13.7	14.8	14.8	15.0
30	8.7	9.8	10.0	10.2
27	13.6	14.5	15.8	15.0
15	10.6	11.0	10.4	10.7

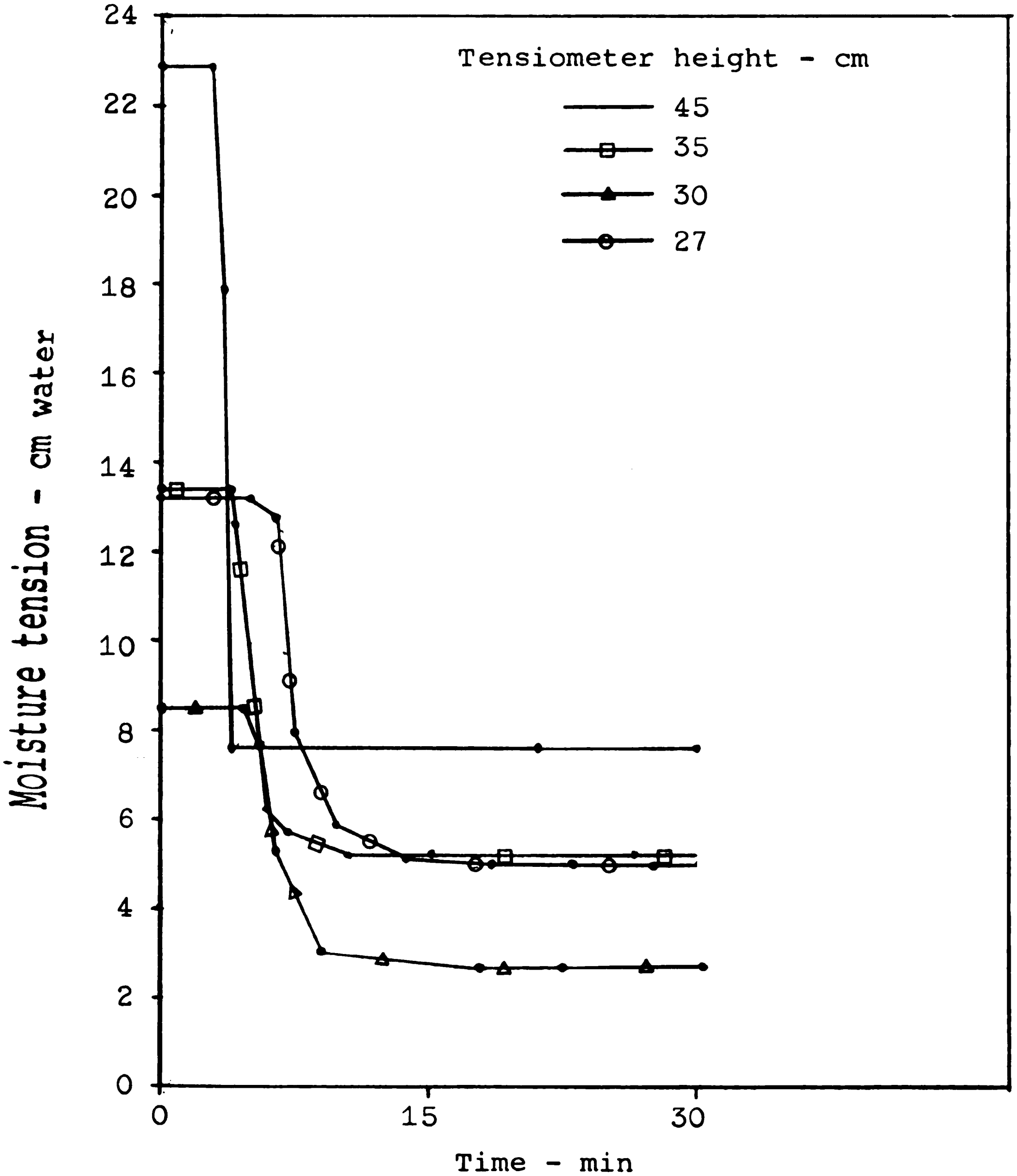


Figure 29. Changes in moisture tension with time in a 3-layered sand column (0.72/1.1/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 60 cc/min.

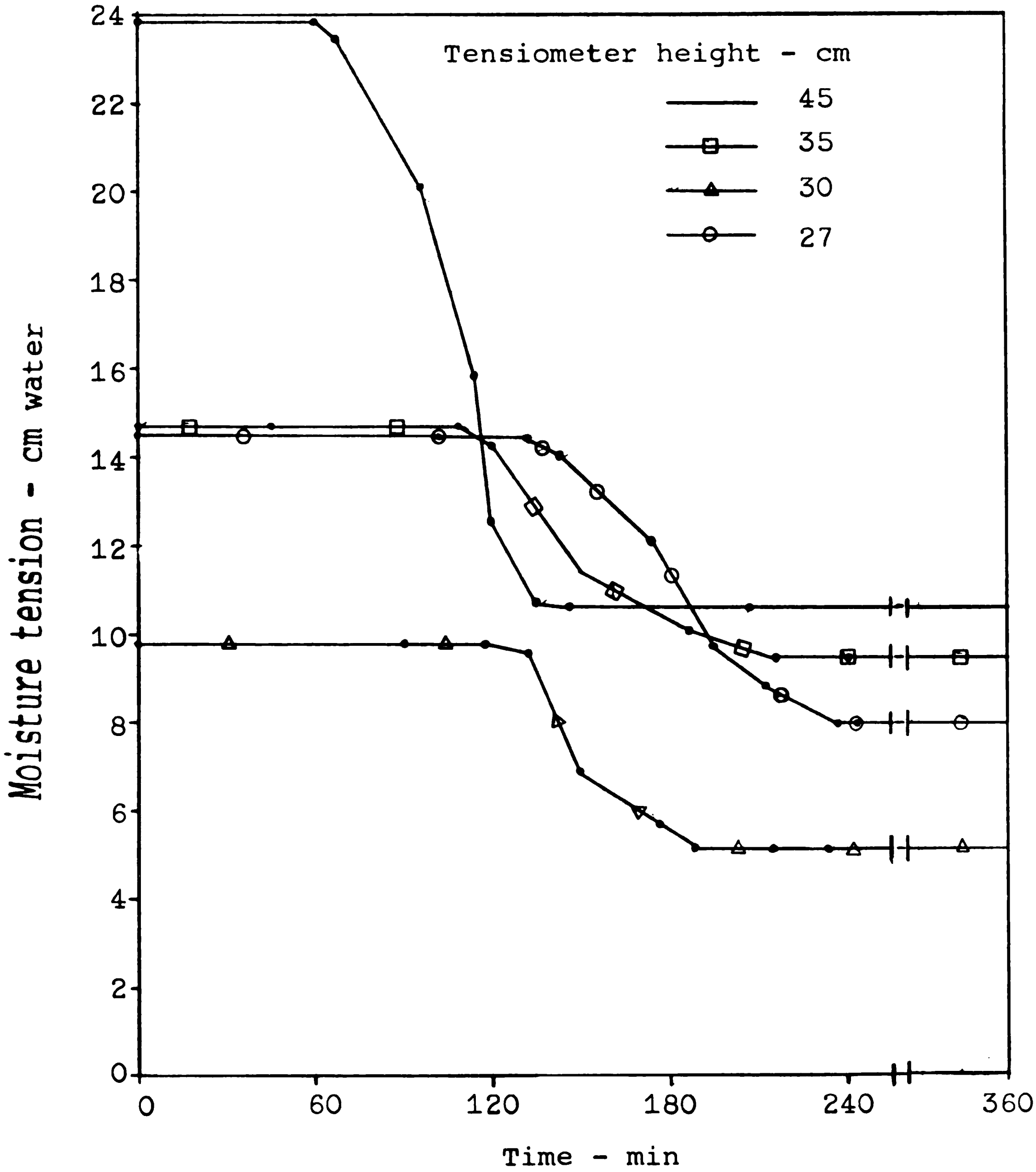


Figure 30. Changes in moisture tension with time in a 3-layered sand column (0.72/1.1/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 1 cc/min.

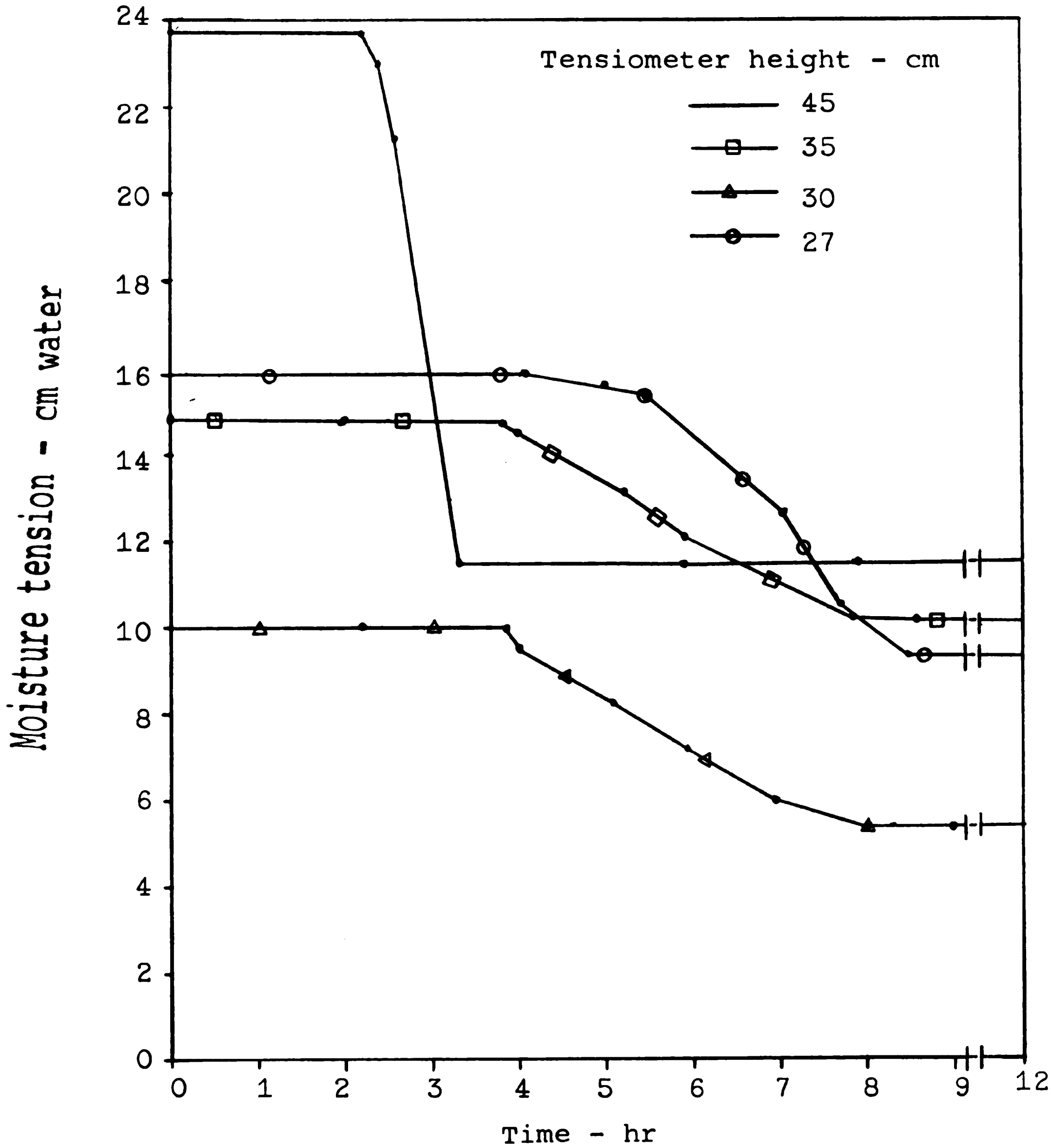


Figure 31. Changes in moisture tension with time in a 3-layered sand column (0.72/1.1/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 0.5 cc/min.

Table 18. Moisture tension distribution in a 3-layered sand column (0.72/0.92/0.72 mm dia, 28 + 1 + 28 cm) as related to varying rates of water application.

Tensiometer height in the column - cm	Rate of water application-cc/min 15	1	0.1	0.05	0.025
	Moisture tension-cm water at initial static condition				
45	23.9	23.6	23.9	----	23.4
35	15.2	15.6	15.3	----	15.6
30	10.9	10.9	11.3	----	10.9
27	13.0	13.6	13.5	----	13.6
15	10.7	10.5	10.5	----	10.5
	Moisture tension-cm water at steady state condition				
45	10.1	10.9	10.8	10.8	11.1
35	7.1	9.3	9.5	9.8	10.7
30	5.6	6.6	7.0	7.5	8.1
27	6.7	8.3	9.4	9.9	10.5
15	8.7	9.5	10.2	10.2	10.2
	Moisture tension-cm water at final static condition				
45	23.6	23.9	----	23.4	23.6
35	15.6	15.3	----	15.6	15.4
30	10.9	11.3	----	10.9	11.1
27	13.6	13.5	----	13.6	13.9
15	10.5	10.5	----	10.5	10.6

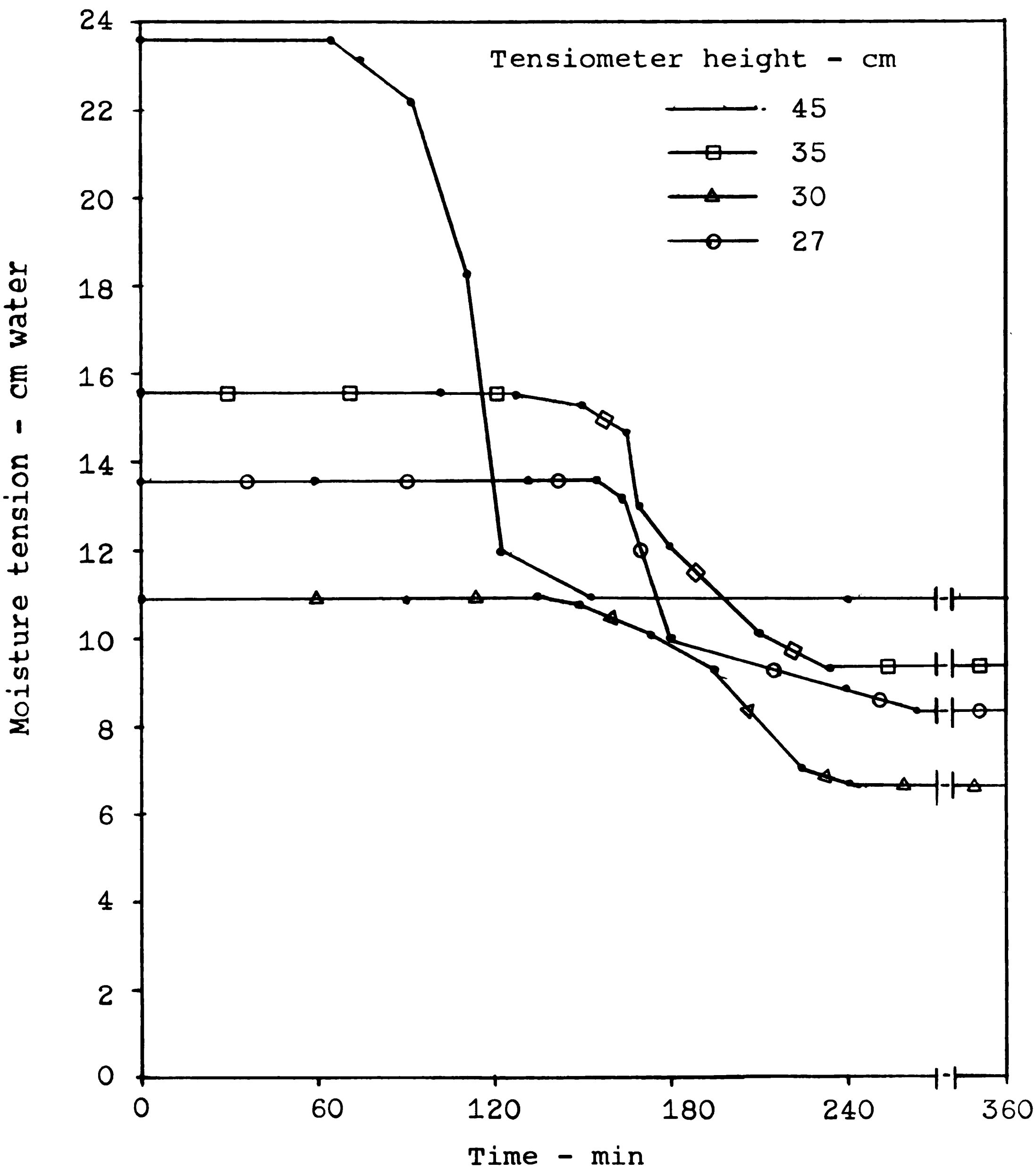


Figure 32. Changes in moisture tension with time in a 3-layered sand column (0.72/0.92/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 1 cc/min.

Table 19. Moisture tension distribution in a 3-layered sand column (0.72/0.46/0.72) mm dia, 28 + 1 + 28 cm) under 2-rates of water application.

Tensiometer height in the column - cm	Rate of water application-cc/min 15	1
	Moisture tension-cm water at initial static condition	
45	22.8	23.4
35	15.5	15.8
30	12.2	12.2
27	12.8	12.8
15	10.5	9.8
	Moisture tension-cm water at steady state condition	
45	10.2	11.2
35	6.4	8.4
30	5.7	6.8
27	5.8	7.0
15	6.8	9.3
	Moisture tension-cm water at final static condition	
45	23.4	23.5
35	15.8	15.8
30	12.2	12.3
27	12.8	12.9
15	9.8	9.9

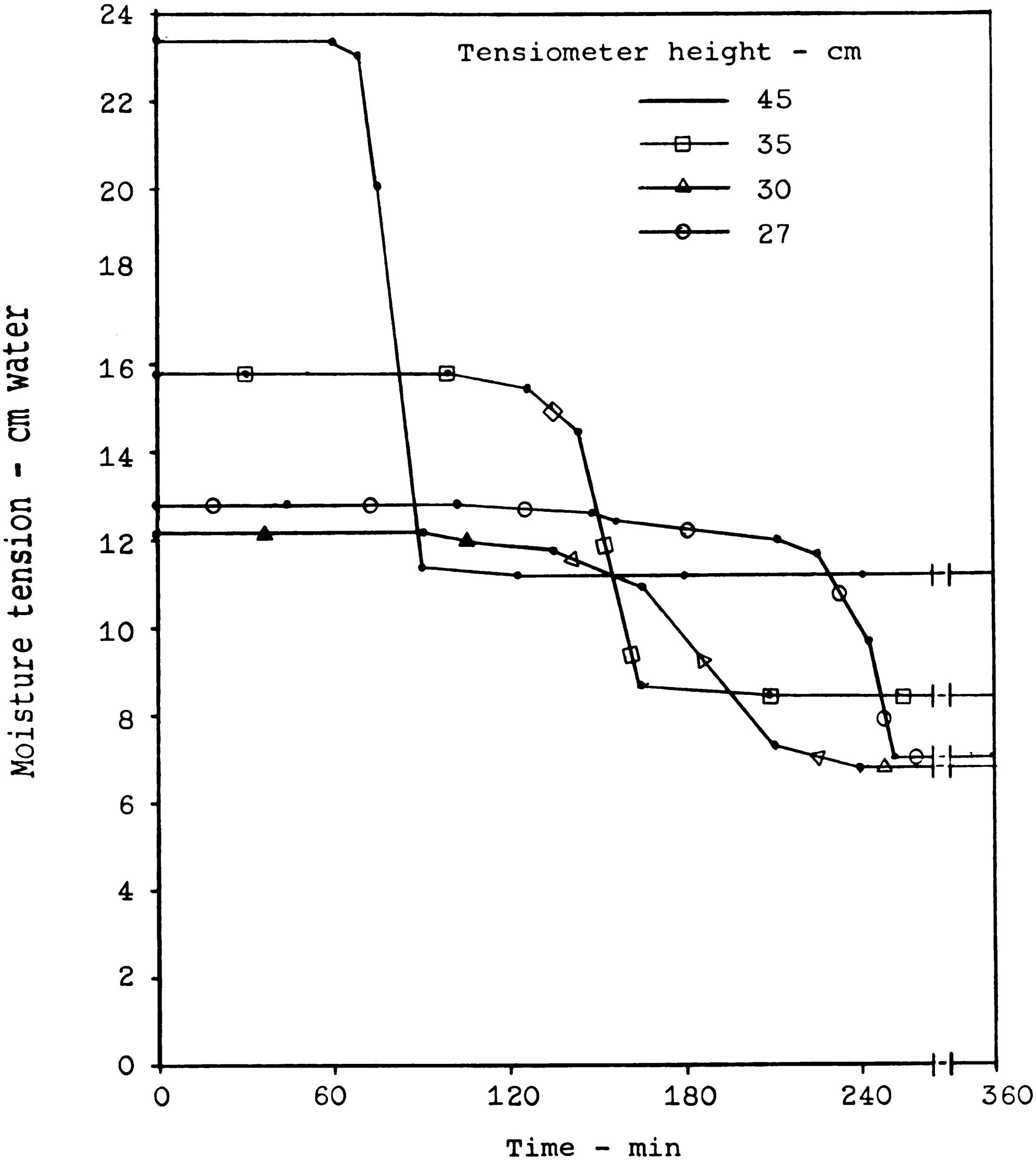


Figure 33. Changes in moisture tension with time in a 3 layered sand column (0.72/0.46/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 1 cc/min.

Table 20. Moisture tension distribution in a 3-layered sand column (0.72/0.37/0.72 mm dia, 28 + 1 + 28 cm) as related to varying rates of water application.

Tensiometer height in the column - cm	Rate of water application-cc/min 15	1	0.1	0.05	0.025
	Moisture tension-cm water at initial static condition				
45	22.6	22.4	22.6	----	----
35	15.1	14.5	15.0	----	----
30	11.8	12.4	12.3	----	----
27	13.6	13.5	13.8	----	----
15	10.0	10.5	10.5	----	----
	Moisture tension-cm water at steady state condition				
45	7.9	11.1	11.3	11.3	11.4
35	4.8	6.9	7.6	7.9	8.1
30	3.8	5.6	6.1	6.4	6.7
27	4.2	6.6	7.3	8.0	8.5
15	5.8	9.3	9.8	9.8	10.1
	Moisture tension-cm water at final static condition				
45	22.4	22.6	----	----	22.3
35	14.5	15.0	----	----	14.9
30	12.4	12.3	----	----	12.3
27	13.5	13.8	----	----	14.0
15	10.5	10.4	----	----	10.4

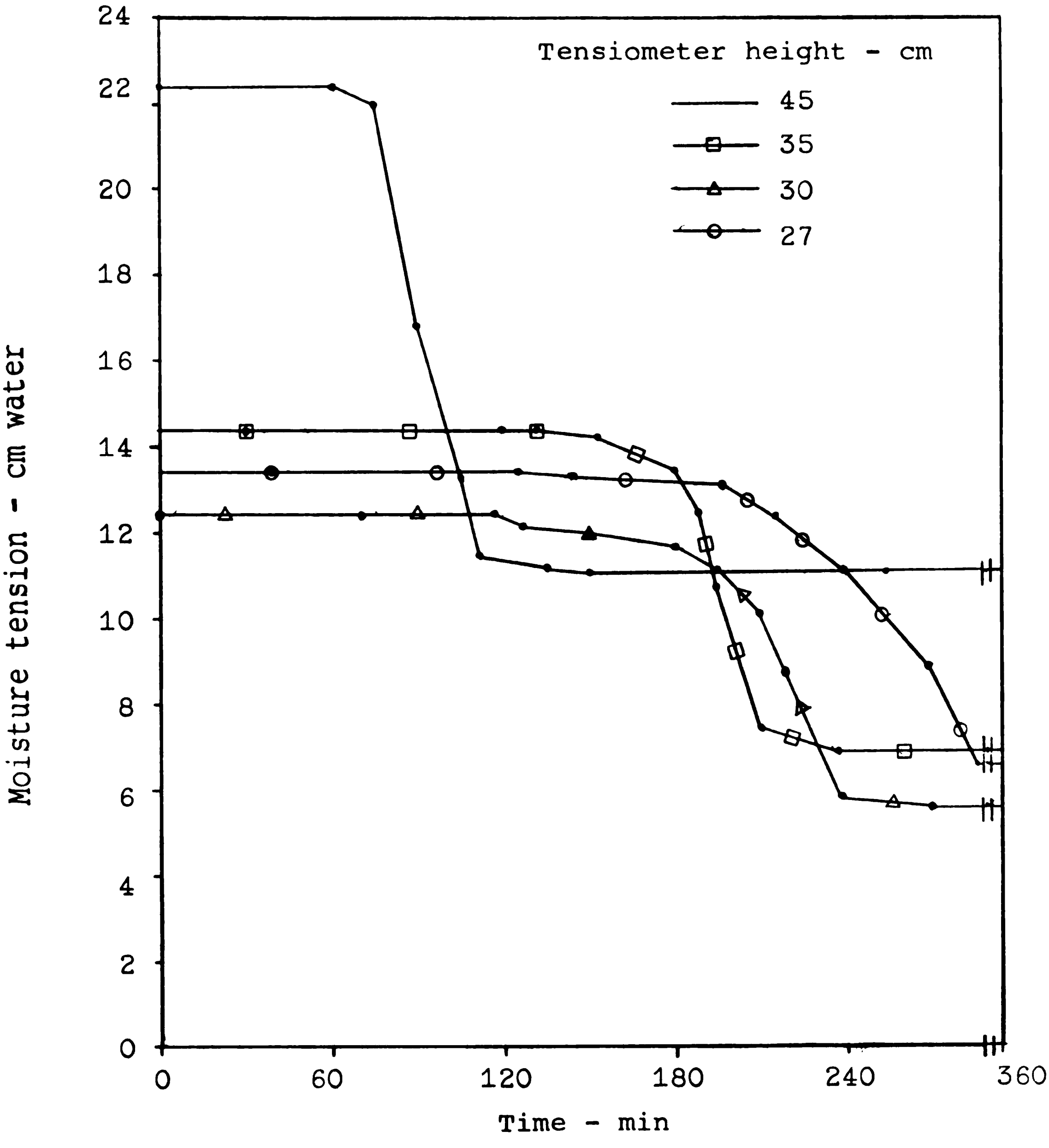


Figure 34. Changes in moisture tension with time in a 3-layered sand column (0.72/0.37/0.72 mm dia, 28 + 1 + 28 cm) during water flow of 1 cc/min.

was changed. The moisture tension of the columns was decreased with increase in rate of water application and it was the lowest with the highest rate of water application.

When the rate of water application of 60 cc/min was used, the tensions changed very fast, and no difference in the time of response of the tensiometers could be observed. Only the column with coarsest stratum showed a complete discontinuity where the observable saturated zone above the stratum increased to 4-5 cm. The moisture tension above the coarse stratum approached zero before or at the time the tension began changing below the stratum. The column with the coarsest stratum (1.55 mm dia) also showed two steady state readings especially in the two tensiometers above and below the stratum. This can be explained on the basis of complete discontinuity. When the wetting front reached the stratum, the moisture tension decreased until enough free water had accumulated to bring the tension to about zero. A few pores were able to connect the capillarity between the two layers and the water moved downward. But the coarse stratum was still acting as a barier and water continued to accumulate above the stratum and positive pressures developed. At this time there was a complete break in the barrier as shown by the sudden change of tension below the layer in figure 23. A complete discontinuity also was observed with the same column with the rate of application of 15 cc/min. All the other columns under all rates of water application showed partial discontinuities but with no positive pressures recorded above the strata.

(3) Particle size of the middle stratum and rate of water application

Particle size of the stratum and rate of water application combined affected the moisture tension distribution in the stratified sand columns.

With higher rate of application (60 and 15 cc/min) and coarser stratum (1.55 mm dia particle size) a complete discontinuity occurred (table 15 and figures 16 and 23). On the other hand, the magnitude of discontinuity decreased as the particle size of the stratum approached the particle size of the main column. Then the discontinuity increased again, as the particle size of the stratum became finer than that of the main column. With a decrease in rate of water application with each column, the moisture tension throughout the column were increased and the magnitude of the discontinuity was decreased.

The time required for the water front to advance and the outflow of water to start increased with the decrease in rate of water application. The data in tables 21 and 22 show the time change sequence for each tensiometer to change and reach the steady state value under two rates of water application. The discontinuities with time are more pronounced with the lowest rate of water application where the delay of

Table 21. Time change sequence of moisture tensions in 3-layered sand columns as related to particle size of middle layer under constant (15 cc/min) rate of water application.

Tensiometer height in the column - cm	Avg. particle size of the middle stratum-mm dia.							
	1.55[1]	1.55[2]	1.3	1.1	0.92	0.72[3]	0.46	0.37
	Time of moisture tension change-min.							
45	5.0	3.5	4.5	9.5	8.0	6.5	10.0	6.5
35	6.5	5.5	10.0	13.5	10.0	12.5	14.0	14.0
30	9.0	6.5	11.0	14.5	14.5	15.0	16.0	15.0
27	13.5	12.5	14.0	18.5	19.5	17.0	20.0	16.0
	Time moisture tension reached steady state-min.							
45	10.0	7.5	12.0	15.0	15.0	12.0	22.5	26.0
35	19.0	17.5	23.0	25.0	24.0	24.0	29.0	24.5
30	22.0	18.0	25.0	27.5	27.0	26.0	30.0	27.5
27	28.0	28.0	27.0	28.0	32.5	28.0	33.0	29.0

[1] 0.2 cm thick middle stratum in 28.4 + 0.2 + 28.4 cm column.

[2] 1 cm thick middle stratum in 28 + 1 + 28 cm.

[3] Uniform sand column.

Table 22. Time change sequence of moisture tensions in 3-layered sand columns as related to varying particle size of the middle layer under constant (1 cc/min) rate of water application.

Tensiometer height in the column - cm	Avg. particle size of the middle stratum-mm dia.							
	1.55[1]	1.55[2]	1.3	1.1	0.92	0.72[3]	0.46	0.37
	Time of moisture tension change-min.							
45	90	56	63	67	69	90	70	75
35	120	98	117	121	138	135	125	132
30	150	102	129	132	149	141	135	150
27	165	190	138	142	162	152	151	165
	Time moisture tension reached steady state-min.							
45	147	111	120	130	152	146	124	135
35	270	207	225	231	239	189	225	236
30	279	214	227	234	249	237	240	263
27	294	265	238	243	264	247	251	285

[1] 0.2 cm thick stratum in a 28.4 + 0.2 + 28.4 cm column.

[2] 1 cm thick stratum in a 28 + 1 + 28 cm column.

[3] Uniform sand column.

water movement through the coarse layer is long. The delay in time was longest with the coarsest layer and then the finest layer with rate of application of 1 cc/min. Furthermore the time required for the change in tensiometer reading above the layer was shortest with the coarsest layer, due to the accumulation of water in this region of the column.

In table 23 the water recovered at the end of the run under two rates of water application (15 and 1 cc/min) is tabulated. The column with the coarsest stratum retained about 13 to 14% of the water added while the percent water retained in the other column ranged only between 2 to 6%.

The difference in time required for the two tensiometers above and below the strata to change and approach steady state values was not significant with the higher rate of water application. The rate of movement of the wetting front and consequently the change of tension was very fast. There was also an increase in time required for the first drop to move out of the column as the particle size of the strata approached the main column's particle size. This is because the rate of movement of water increases as the moisture content increases and the column with the greatest discontinuity was wettest at the high rate of water application.

When the rate of water application decreased the time difference for the two tensiometers above and below the strata to change became greater as the particle size of the

Table 23. Water recovery and the time required for outflow of water to start in 3-layered sand columns as related to varying particle size of the stratum under 2-rates of water application.

Observations	Avg. particle size of the middle stratum-mm-dia.					
	1.55[1]	1.55[2]	1.3	1.1	0.92	0.46
Rate of water application	15 cc/min					
Total volume of water added	900 cc/60 min.					
Total volume of water recovered-cc/24 hr.	875	787	861	880	878	866
Total volume of water recovered-%	97.2	87.4	95.7	97.8	97.6	96.2
Time required for the outflow of water to start-min	23	22	23	28	29	28

[1]Middle stratum 0.2 cm thick.

[2]Middle stratum 1 cm thick.

0.37	1.55[1]	1.55[2]	1.3	1.1	0.92	0.46	0.37
	1 cc/min.						
	360 cc/360 min.						
854.5	347	310	341	350	349	340	339
95	96.4	86.1	94.7	97.2	97.1	94.5	94.1
27	200	267	210	200	208	255	255

strata increased. This was due to the restriction of the strata for the downward movement of water until a point was reached where the coarse strata allowed the movement of water. This time lapse caused the increase in time required for the outflow of water to start in columns with strata of large particle sizes. This time required was decreased until the particle size of the column approached uniformity (tables 21, 22 and 23).

(4) Thickenss of the middle stratum

In order for the layer of coarse sand to act as a barrier and affect the moisture tension distribution a minimum thickness of layer is required. This thickness will vary with ratio of particle size of the adjacent layers in the column. Theoretically, a monolayer of spherical particles should be enough. But because of irregularity of sand particles, the thickness and uniformity of this layer becomes more critical.

An experiment was designed where different layer thicknesses were compared. The average particle size, thickness of layer and rate of water application that were used are listed below:

Avg. particle size-mm dia Top	middle	bottom	Thickness of the layer-cm	Rate of water application-cc/min
0.72	1.55	0.72	1.0	15 and 1
0.72	1.55	0.72	0.2	15 and 1
0.63	1.34	0.63	4.0	3
0.63	1.34	0.63	2.0	3

The results of the experiments are reported in table 24 and figures 35, 36 and 37, which show the moisture tension distribution in the sand columns with 0.2 cm thick strata. The data show the same trend of decrease in moisture tension through the column. The distribution of moisture tension is lower with the higher rate of water application. The data obtained with the 1 cm stratum of the same particle size and under the same rate of water application were compared. The results, as shown in figure 37 indicate a decrease in magnitude of the discontinuity with decrease in thickness of the coarse stratum with both rates of water application. Furthermore, no positive pressure was developed above the stratum with 0.2 cm thickness.

The results of experiments with 4 and 2 cm strata of average particle size of 1.34 cm dia are presented in table 25 and figures 38 and 39. Increasing the thickness of the stratum did not decrease the moisture tension in the column by the same ratio. The difference in moisture tension at the bottom of the coarse stratum is due to difference in location of the tensiometer.

Table 24. Moisture tension distribution in a stratified sand column (0.72/1.55/0.72 mm dia, 28.4 + 0.2 + 28.4 cm) under 2-rates of water application.

Tensiometer height in the column - cm	Rate of water application - cc/min 15	1
	Moisture tension-cm water at initial static condition	
45	22.9	23.3
35	16.3	15.7
30	12.4	12.3
27	15.2	14.8
15	9.8	9.7
	Moisture tension-cm water at steady state condition	
45	8.4	10.4
35	3.0	7.0
30	2.0	4.9
27	3.3	7.3
15	2.9	9.0
	Moisture tension-cm water at final static condition	
45	23.3	23.5
35	15.7	15.8
30	12.3	12.3
27	14.8	15.0
15	9.7	10.0

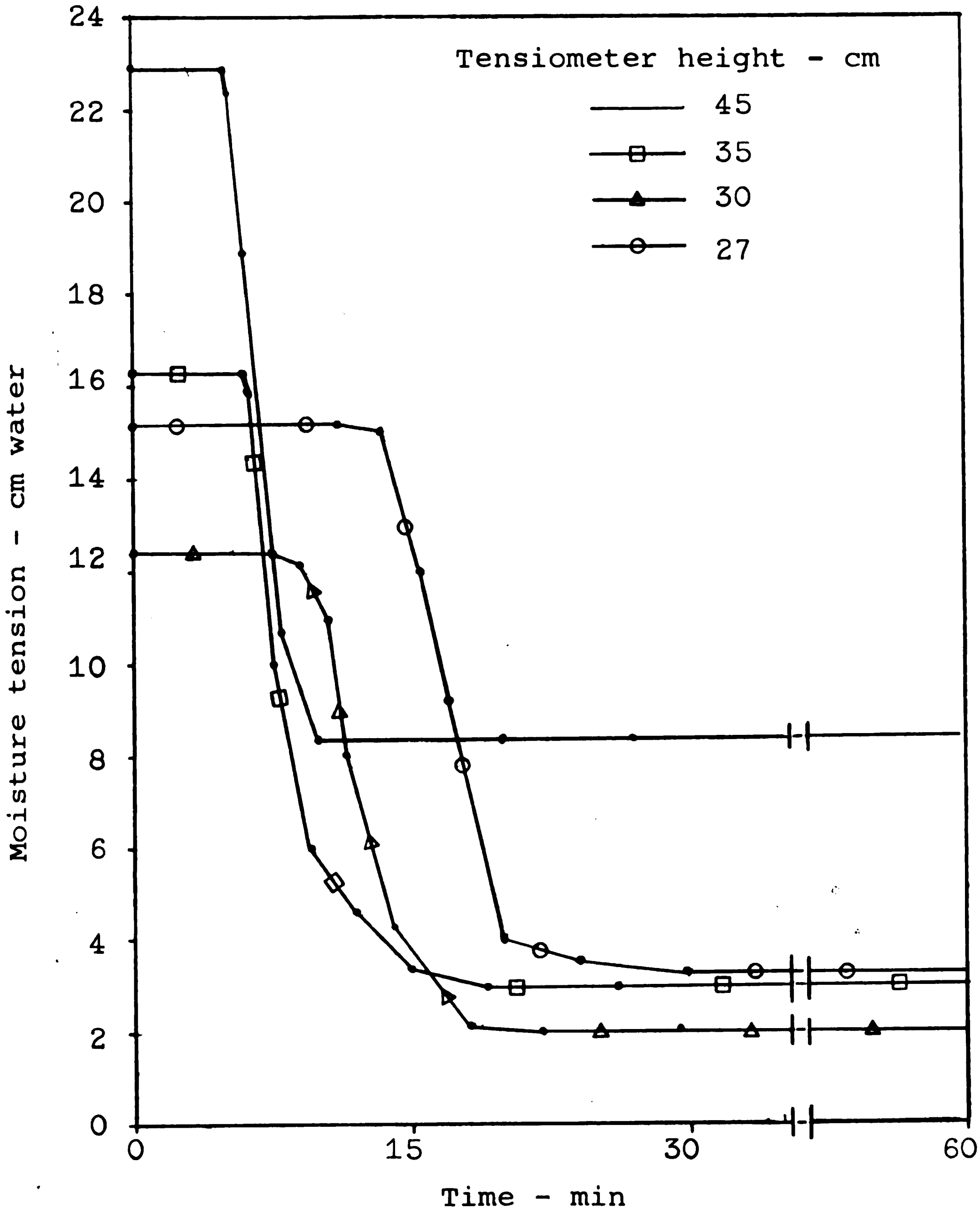


Figure 35. Changes in moisture tension with time in a 3-layered sand column (0.72/1.55/0.72 mm dia, 28.4 + 0.2 + 28.4 cm) during water flow of 15 cc/min.

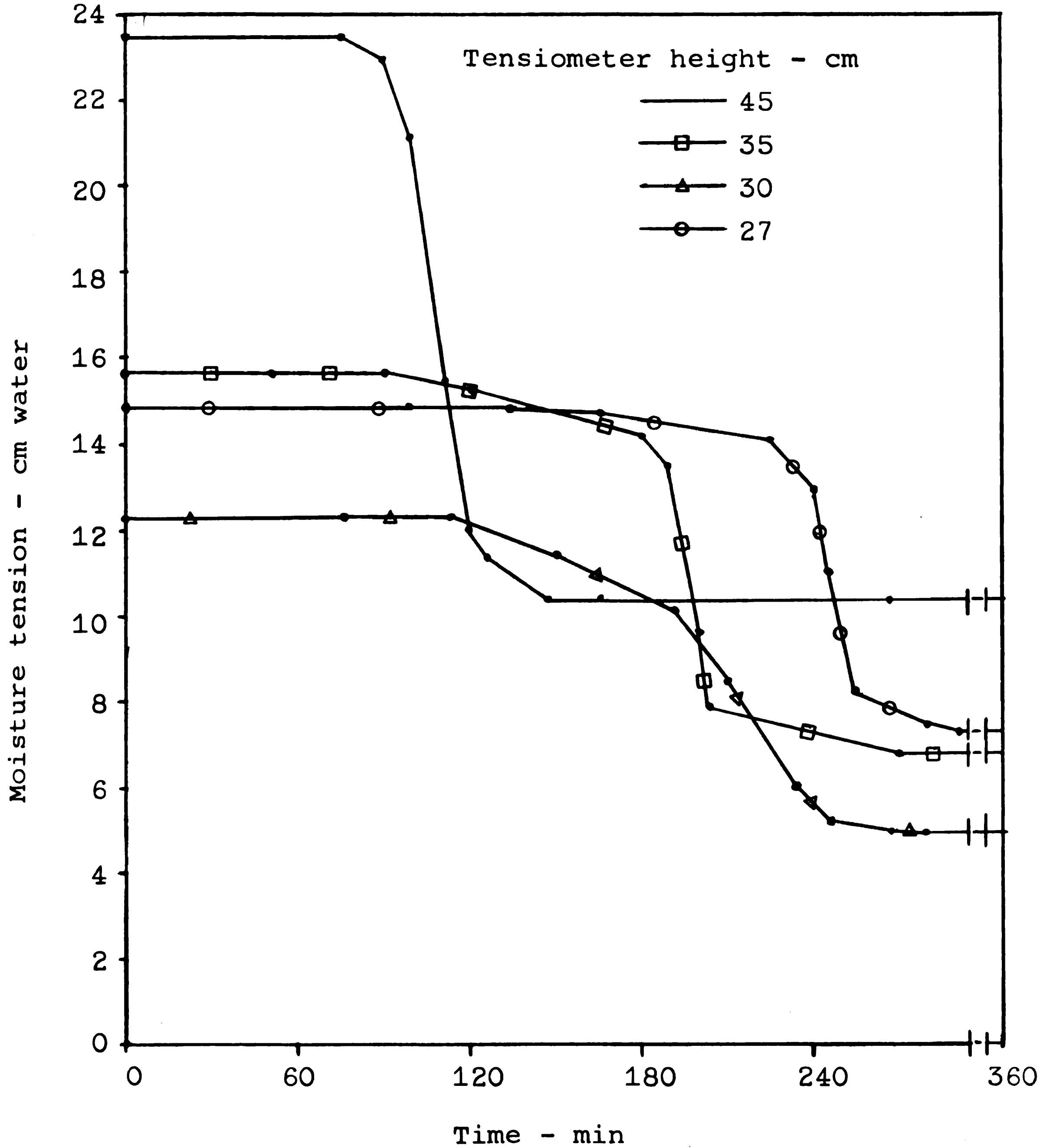


Figure 36. Changes in moisture tension with time in a 3-layered sand column (0.72/1.55/0.72 mm dia, 28.4 + 0.2 + 28.4 cm) during water flow of 1 cc/min.

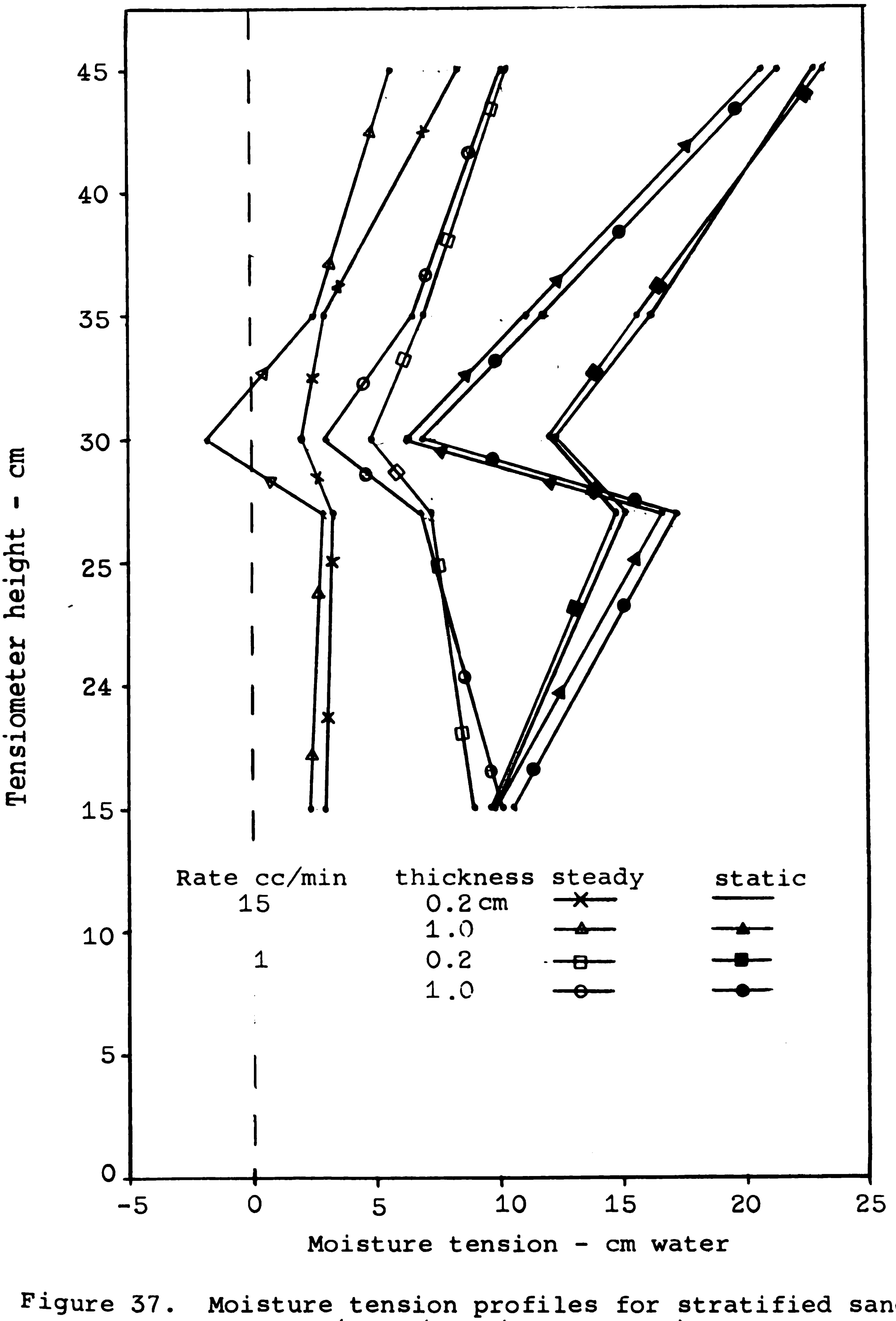


Figure 37. Moisture tension profiles for stratified sand columns (0.72/1.55/0.72 mm dia) as affected by the thickness of the middle stratum under 2-rates of water application.

Table 25. Moisture tension distribution in stratified sand columns (0.63/1.34/0.63 mm dia) as affected by the thickness of the middle stratum under constant (3 cc/min) rate of water application.

Tensiometer height in the column - cm	Thickness of the stratum - cm 4[1]	2[2]
	Moisture tension-cm water at initial static condition	
45	21.7	21.1
35	12.5	12.1
30	6.7	6.5
27	----	17.2
24	15.8	----
15	10.8	10.6
	Moisture tension-cm water at steady state condition	
45	9.8	10.4
35	7.0	7.3
30	2.3	2.6
27	----	7.6
24	7.2	----
15	9.7	9.7
	Moisture tension-cm water at final static condition	
45	21.7	20.7
35	12.6	12.2
30	6.9	6.7
27	----	17.4
24	15.9	----
15	10.6	10.4

[1] 25 + 4 + 25 cm height of the column.

[2] 27.5 + 2 + 27.5 cm height of the column.

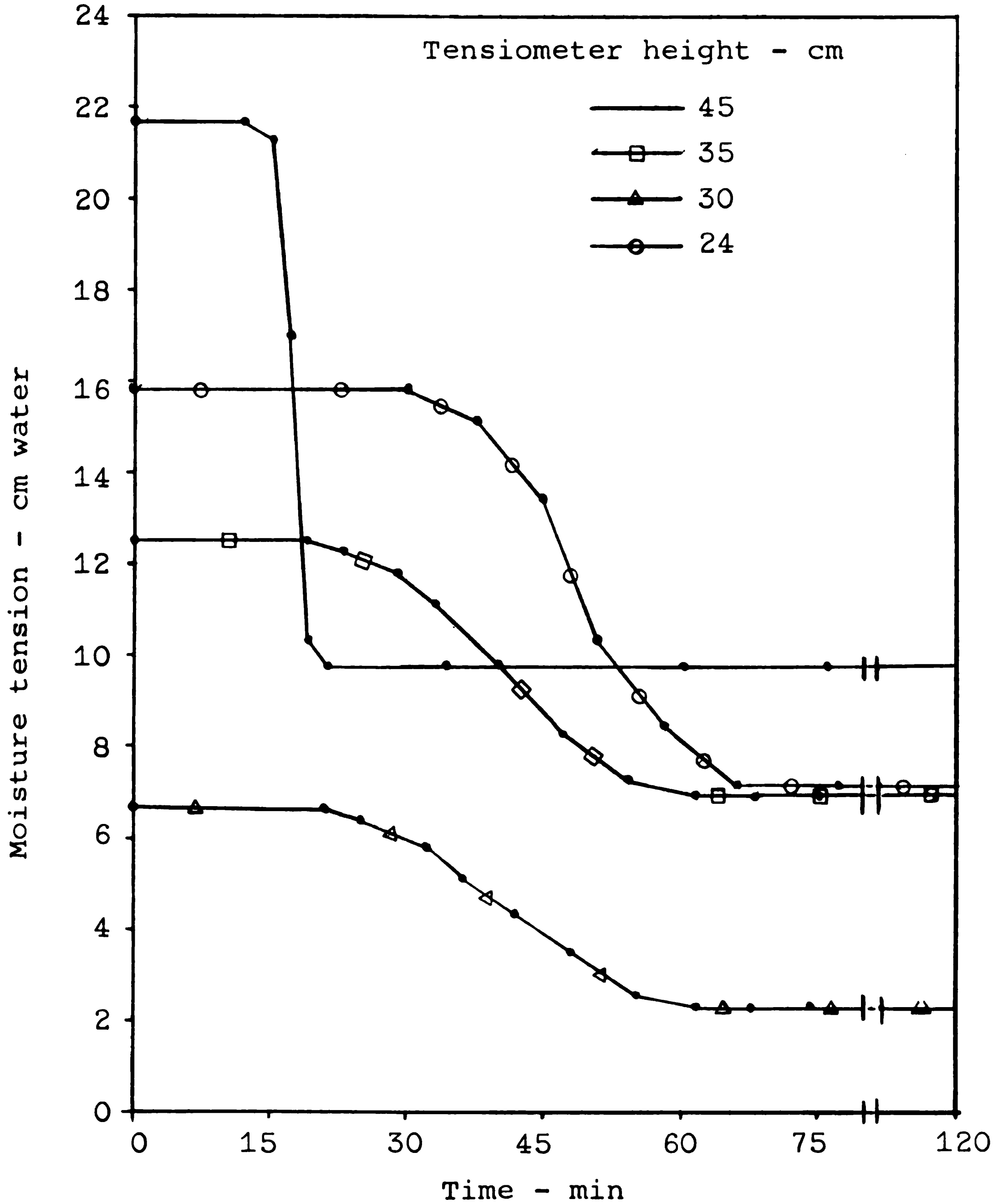


Figure 38. Changes in moisture tension with time in a 3-layered sand column (0.63/1.34/0.63 mm dia, 25 + 4 + 25 cm) during water flow of 3 cc/min.

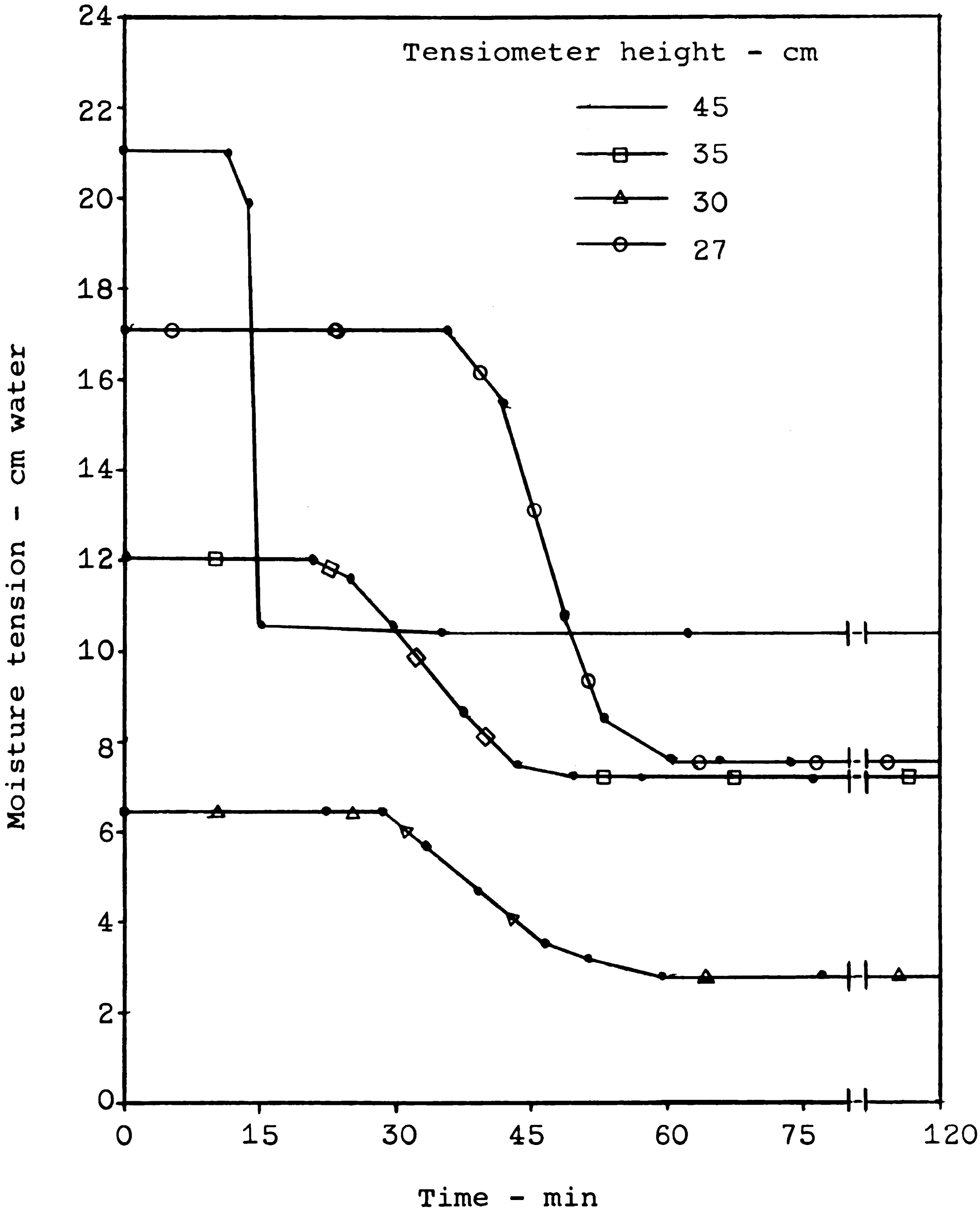


Figure 39. Changes in moisture tension with time in a 3-layered sand column (0.63/1.34/0.63 mm dia, 27.5 + 2 + 27.5 cm during water flow of 3 cc/min.

V. DISCUSSION

A. Particle size of the middle strata in relation to discontinuities.

The data presented in tables 13-20 and figures 16-34 show that the movement of moisture in the stratified sand separates will be affected whether the particle sizes change from fine to coarse or the reverse. This result is contrary to the results obtained by Colman and Bodman (6) and the theoretical studies by Scott and Corey (41) and Hanks and Bowers (16), where they concluded that the least permeable layer restricts the downward movement of water in the column. The conditions in this thesis differs from that of Colman and Bodman because they studied the moisture movement in natural soil under flooded conditions. Their soils had a wider range of particles and pore sizes and may have had some structure. Scott and Corey (41) used hydrocarbon liquid (Soltrol) instead of water in their studies, and the results are only of the drainage cycle. Hanks and Bowers (16) only concluded that theoretical results were in agreement with experimental data obtained by Colman and Bodman (6).

Discontinuities were found to be a function of particle size of the strata. The greater the difference between the particle size of the two layers, the greater the magnitude of the discontinuity in the stratified sand columns. This is evidenced from the data shown in table 15 and figures 40 and 41. Similar data were obtained by Miller and Gardner (33) where they studied infiltration rate with time. They concluded that the rate of infiltration was lowest with the greatest difference in particle size where sand was overlain by a silt loam soil. Eagleman and Jamison (9) also showed the restriction of drainage by the coarse layer in stratified soil. While their experimental conditions and soils are different from this experiment, nevertheless, the results obtained in this study agree with theirs.

In this study, water movement in stratified sand, as well as in uniform sand material, included the study of two processes: First, the capillary rise from water table upward through the sand and; second, the infiltration of applied water from surface down through the sand. The results of these two processes will be discussed separately and then the relationship between the two processes will be discussed.

The values for height of capillary rise of water in uniform and stratified sand (tables 2 and 3) suggest that these heights are related to (1) the particle size of the sand separates, (2) the arrangement of the layers as whether the particle size became coarser from bottom to top or the reverse and (3) the thickness of these layers.

The height of capillary rise in the sand separates increased with a decrease in their particle size. In

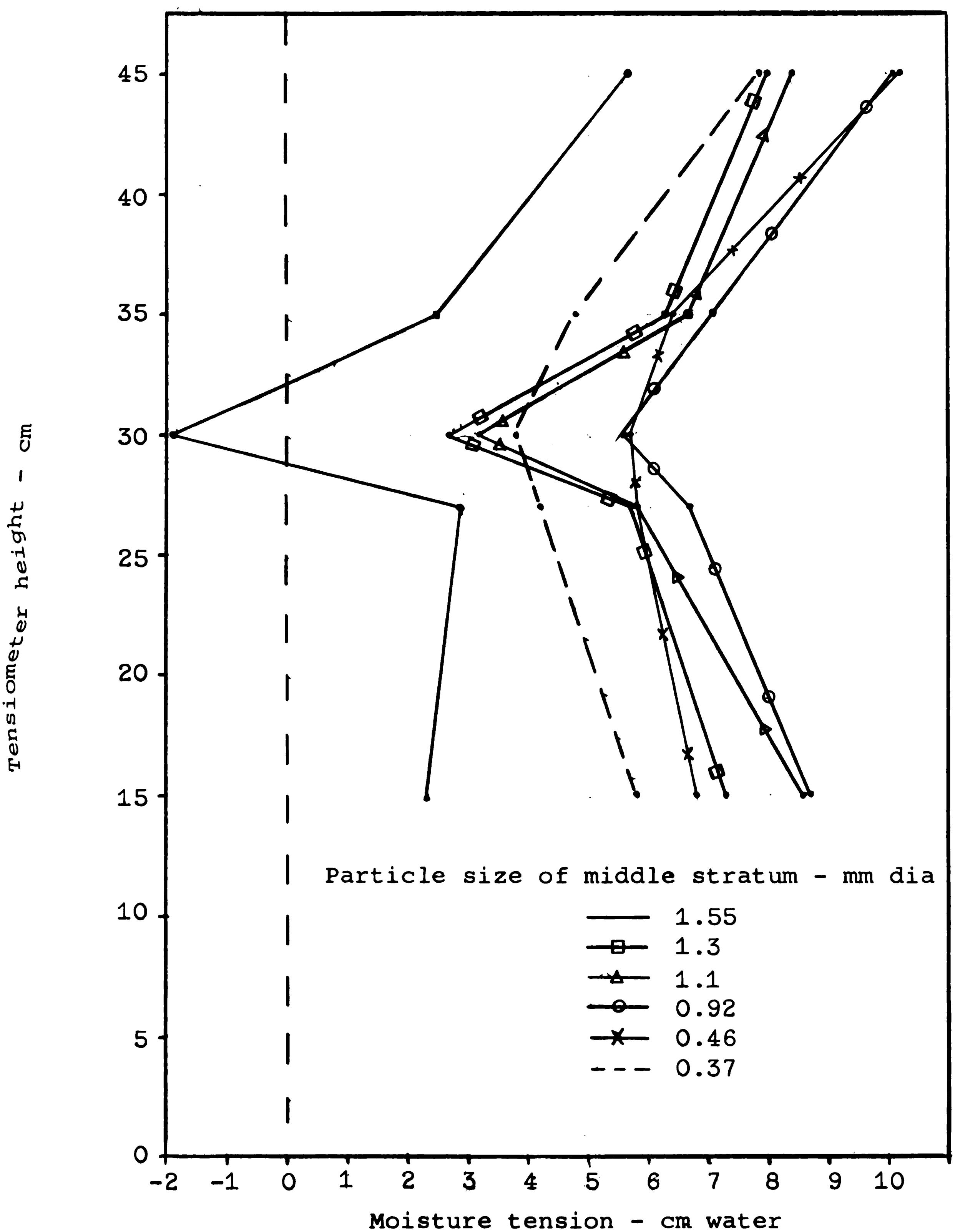


Figure 40. Moisture tension profiles for stratified sand columns during water flow (15 cc/min) as related to varying particle size in the middle stratum under steady state conditions.

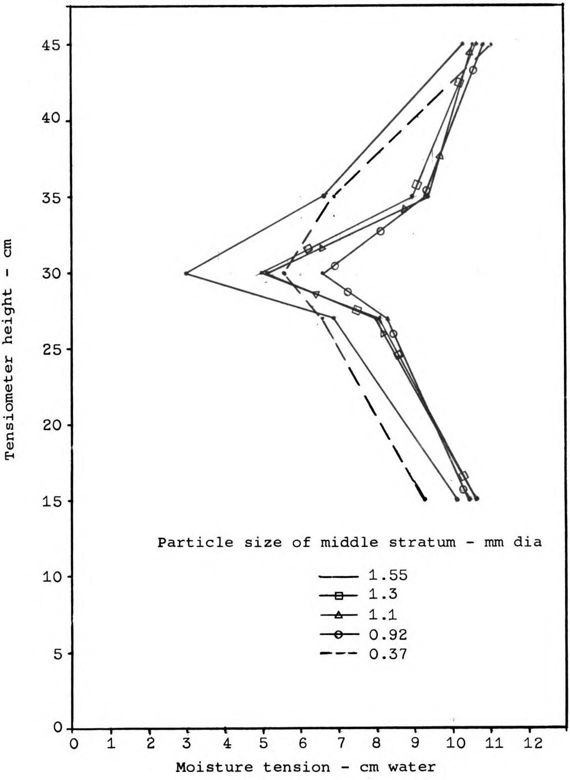


Figure 41. Moisture tension profiles for stratified sand columns during water flow (1 cc/min) as related to varying particle size in the middle stratum under steady state conditions.

stratified sand the height of capillary rise was affected whether the column becomes coarser or finer from bottom upward. The restriction in capillary rise in stratified sands was related to the particle size of the two layers forming the column and their thickness. Because of the low heights of capillary rise in coarse sand separates compared to fine sand separates, the maximum height of capillary rise in the coarse sand layer, controls the total height of capillary rise in stratified sands. If the thickness of the lower coarse layer was within its maximum capillary rise region, the coarse layer does not affect the capillary rise height of fine layer above it. But when the thickness of the lower coarse layer is greater than its maximum capillary rise, then the capillary rise will stop at this point. On the other hand, when the thickness of the lower fine layer is within the maximum capillary rise of the coarse layer then the water will move upward to the maximum capillary rise of the coarse layer. This explains why the capillary rise in fine sand material will stop at the boundary line between the lower fine layer and the coarse layer above it no matter how high the capillary rise is in the uniform fine layer.

When water is applied to a sand column where a fine sand layer was underlain by a coarse sand strata as in tables 15-18 and figures 40,41, the applied water moves downward as a wetting front until it reaches the coarse strata. At the interface of the two layers a change in particle size and pore size occurred where the small pores and particles contact the large pores and particles of the coarse strata. As a result, the coarse strata is incapable of conducting water at the high moisture tension which exists at the point of contact and this stops the movement of the wetting front. In order for the wetting front to continue moving downward, the moisture tension at the contact point must decrease by water accumulation until the tension is low enough to allow water to pass through the pores and around the particles of the coarse strata. Probably it is necessary for the coarse sand to wet in only a few places and the moisture movement occurs first through a few water filled pores. As the water moves into the fine sand below, the greater attration of the fine sand for water causes the continuation of moisture movement. As the fine sand below the coarse strata is wetted to greater depths the water transmission rate is reduced and the coarse sand in the intervening layer becomes wetter.

As the particle size of stratum approaches the particle size of the main column the effect of the stratum on the magnitude of discontinuity decreases. But when the particle and pore size of the stratum becomes finer than of the main column (tables 19, 20 and figures 40 and 41) the wetting front moves downward when it contacts the fine particles and pores of fine stratum. The fine pores fill rapidly because of their greater attraction for water. The wetting front advances through the fine layer without restriction, but when the wetting front in the fine stratum contacts the coarse layer underlying it, the same conditions exist as in the previous case when a coarse stratum was lying between the two fine layers.

The experimental results and the discussion above demonstrate that in stratified sand the coarse strata govern the movement of soil moisture.

Restriction of the moisture movement from the finer sand above the coarse stratum results in accumulation of moisture above this layer (tables 7, 14 and figure 22) similar to the data obtained by Miller and Bunger (32). The amount and height of the moisture accumulated above the coarse layer is a function of the difference between the particle size of the coarse layer and the fine layer above it. The greater the differences between the particle size of the two layers the more the moisture accumulates above the coarse layer. The results of moisture tension studies on core samples (tables 26-31 in the appendix and figure 7), also indicated that the accumulation of moisture was highest when the ratio of particle size of the fine to coarse layer was about 1 to 5. Similar ratios of particle size have been suggested in the construction of putting greens for golf courses (12, 18, 36 and 44). There is however, a limit to the difference in particle size of the two layers that is necessary to cause a discontinuity in moisture movement and distribution in stratified sands. This limit occurs when the difference in particle size approaches a point where the fine particles fall between the large pores of the large particles and a mixed interlayer is formed, which have the characteristics of both layers (37). Under field condition, a multitude of different conditions can and do prevail.

From the previous discussions it was established that the particle size distribution of sand separates effects both upward and downward movement of water in stratified sands. Furthermore it was suggested that the coarse layer governed the movement of water in both processes. The capillary rise and the infiltration processes in uniform and stratified sand column are related. To illustrate this relationship figure 42 was developed by plotting the experimental data of moisture tension distribution for the following columns: (1) Uniform coarse sand of 1.34 mm particle size, (2) uniform fine sand of 0.38 mm particle size, (3) 2-layer stratified sand with a fine layer overlying a coarse layer sand and (4) 3-layer stratified sand with a 4 cm coarse stratum interposed on a fine sand column. A 1/1 slope line was drawn to represent the area where a true capillary rise would occur. The moisture tension values at lower uniform sand were extrapolated to the 1/1 line. The points of intersection were at 8.0, 12.5, 7.6 and 13.0 cm respectively. These values are equivalent to the height of capillary rise in each sand separate. The difference between the values 7.6 and 8.0 for the coarse sand, 12.5 and

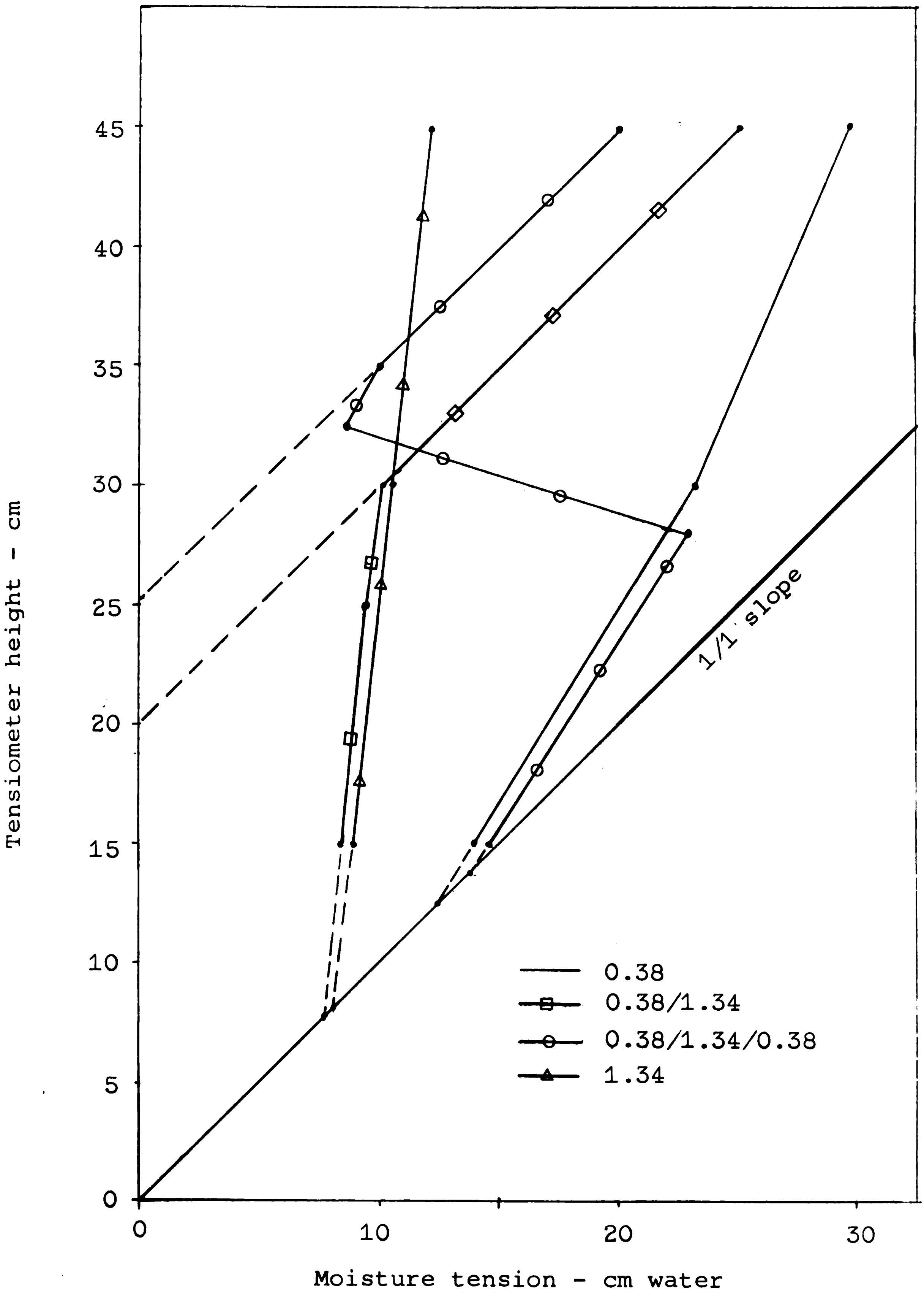


Figure 42. Moisture tension profiles of uniform, 2-layered and 3-layered sand columns (0.38, 1.34, 0.38/1.34 and 0.38/1.34/0.38 mm dia respectively) under static conditions.

13.0 for the fine sand are not significantly different and the difference could be due to difference in packing of the columns. The capillary rise values obtained in a separate experiment of 6.5 and 13.6 (table 8) agrees with these values. After the capillary rise reaches its maximum height at the point of intersection, the moisture tension values do not follow the 1/1 slope line due to the break in capillarity.

In the stratified sand columns the bottom fine sand has not reached field capacity at the contact with the coarse layer. Nevertheless, the tension at this point is much greater than the maximum capillary rise of the coarse sand. Therefore, the coarse sand has been drained to the tension where its capillary conductivity approaches zero. The tension at the top of the coarse stratum is therefore less than that of the fine sand below. The fine sand immediately above the coarse layer has a tension equivalent to the tension existing in the coarse sand layer immediately below it which is in the range of capillary rise of the fine sand. In this way the coarse stratum has caused a drop or discontinuity in the tension distribution in the stratified column. In these cases the fine sand above the coarse stratum has a tension distribution similar to what it would have if the water table were at 25 cm above the bottom of the column for the three layer column or 20 cm in the two layer column.

The height of the observed saturated region above the coarse layer is related to the capillary rise. Data obtained in this study (table 12) to illustrate the relation between capillary rise in uniform sand separates and the height of accumulated water above the coarse layer in stratified sand columns suggest similar trend as suggested by Staprens (29). The data indicates that the height of accumulated water above the coarse layer is equal to the difference in capillary rise of the two sand separates forming the stratified column. The greater the difference in particle size of the two layers, the greater is the height of accumulated water.

The experimental data of moisture tension distribution in the fine layer overlying a coarse layer, indicated that in order for the infiltrated water to move downward through the coarse layer, the tension must be lowered at the contact point by accumulation of water above the coarse sand (tables 7 and 14). This is contrary to the data obtained in moisture tension studies on core samples (tables 26-31 in the appendix) and the data obtained by Nelson and Baver (37) where the data indicated that no appreciable amount of water was removed from the system until the tension necessary to start the drainage of the fine layer was reached. The experimental data in both cases are true if it is realized that in the first case the water was moving in unsaturated conditions, while in the later case the water was draining from a saturated condition and the pores of the coarse layer were filled with water.

B. Proposed mechanism of flow in stratified sand.

A mechanism based on the phenomena of surface tension and capillary rise is proposed. This mechanism describes the movement of moisture in a stratified sand column where a fine sand layer is underlain by a coarse sand layer.

The existence of a surface tension across a curved water surface results in a difference in pressure, the pressure being greater on the concave side than on the convex side. This is expressed by equation:

$$P_C = \frac{2\gamma}{R} \qquad (1)$$

Equation 1 describes the relation between the tension or pressure defficiency (P) in capillary water, the surface tension (γ) of the water and the radius of the curvature (R) of the meniscus in a circular capillary tube in which the meniscus is a segment of a sphere having the same curvature at all points (Moore 35 and Sprangler 42).

The occurrence of a concave meniscus leads to a capillary rise. Water rises in the capillaries until the weight of the water column balances the pressure difference of the two sides of the meniscus.

In figure 43 a capillary tube whose radius r is sufficiently small that the surface of the meniscus can be taken as a section of a sphere with radius R.

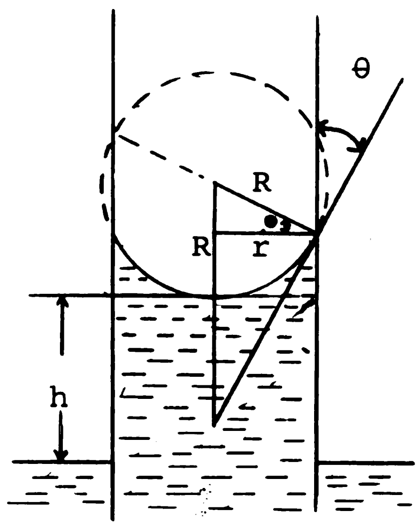


Figure 43. Curvature of water surface (meniscus) in a capillary tube.

In figure 42 cos Θ = r/R, then substituting for R, equation 1 becomes:

$$P_c = \frac{2\gamma \cos \theta}{r} \qquad (2)$$

If (h) is capillary rise of water and (ρ) is the density of water, then the weight of the cylinderical water column is ($\pi r^2 h \ \rho \ g$), or the force per unit area balancing the pressure difference of the two sides of the meniscus is equal to ($h \cdot \rho g$) where (g) is the gravitational force.

$$\text{Therefore} \quad h\rho g = P_c = \frac{2\gamma \cos \theta}{r}$$

$$\text{and} \quad h = \frac{2\gamma \cos \theta}{r\rho g} \tag{3}$$

But for water, on most soil minerals, $\theta = 0$, and the radius of curvature equal to the radius of the capillary tube.

$$\text{Then} \quad h = \frac{2\gamma}{r\rho g} \tag{4}$$

Equation 4 is the capillary rise equation which shows that the capillary rise varies with the radius of the capillary tube. In other words as the radius of capillary tube becomes smaller the radius of the curvature becomes smaller too and consequently the height of capillary water will be higher and the tension or pressure deficiency of capillary water to balance this height becomes greater (figure 44).

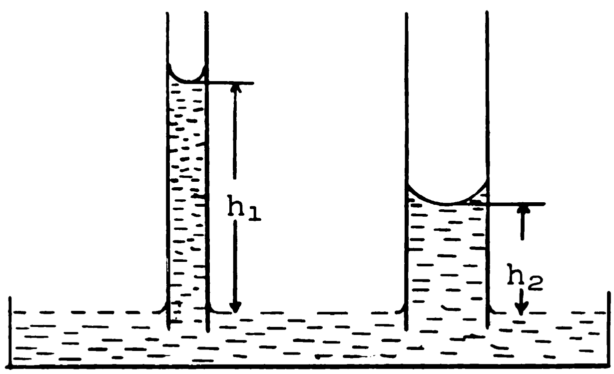


Figure 44. Height of capillary rise in relation to the radius of the capillary tube.

In a tube that is not circular, and particularly in a soil capillary, the meniscus is not spherical in shape, but it may be a warped or saddle-shaped surface having different curvatures. The equation for soil water tension in such a case is:

$$P_c = \gamma \left(\frac{1}{R_1} \pm \frac{1}{R_2}\right) \quad (5)$$

in which R_1 and R_2 are radii of the curvature of a warped surface in two principle planes as shown in Figure 44. (Positive sign is for synclastic surface where R_1 and R_2 are positive and the negative sign is for anticlastic surface where R_1 is negative and R_2 is positive.)

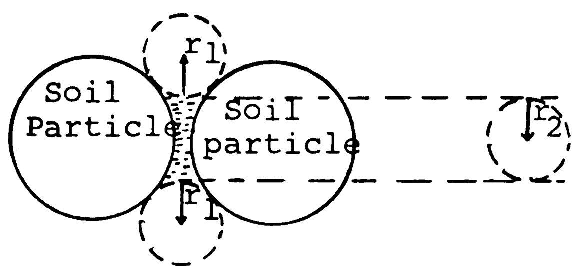


Figure 45. Water between two soil particles.

When water is applied to the layered sand column, the wetting front moves downward in the fine layer until it reaches the coarse stratum. At the interface of the two layers a change in particle size and pore size occurs where the small pores and particles contact the large pores and particles of the coarse stratum. Because the coarse stratum is incapable of conducting water at the high tension which exists at the interface of the two layers the wetting front advance stops. This is a result of inequality in curvature between the upper and lower menisci, the upper meniscus radius of curvature R_1 is smaller. The forces acting upon the water above the coarse stratum are:

1. Force of gravity which is equal to the weight of the water per unit area $h\rho g/cm^2$ directed downward.
2. The tension under the upper meniscus which is equal to $\frac{2\gamma}{R_1}$ directed upward.
3. The tension under lower meniscus which is equal to $\frac{2\gamma}{R_2}$ directed downward.

then $$h\rho g + \frac{2\gamma}{R_2} = \frac{2\gamma}{R_1}$$

and $$h\rho g = \frac{2\gamma}{R_1} - \frac{2\gamma}{R_2} \qquad (6)$$

The resulting difference of the forces will be directed upward supporting the accumulated water above the coarse stratum.

In order for the wetting front to continue downward, the moisture tension at the interface must decrease by further increase in height of water accumulation (h) above the coarse stratum. But an increase in the value of (h) must be counterbalanced by an increase in the value of $\frac{2\gamma}{R_1} - \frac{2\gamma}{R_2}$. In equation (6) γ is constant and R_1 is constant too because as a curved surface is displaced parallel to itself to a new position, its area will change in order for the R_1 to remain the same (35). The value $\frac{1}{R_2}$ must change and decrease, that is the curvature of the lower meniscus decreases where $\frac{1}{R_2}$ approaches zero as R_2 approaches infinity. At this point the moisture tension at the interface approaches zero and will be equal to atmospheric pressure. Equation 6 reduces to:

$$h' = \frac{2\gamma}{R_1 \rho g} \quad (7)$$

Equation 7 is the same as equation 4 which is the capillary rise equation. Examining a cross section of the infiltration column at the interface in relation to a capillary rise from the free water table as shown in Figure 46, the pressure at the bottom of both columns are zero.

If a small increment of water (one drop) is added to the top of each column the systems will change. In the capillary rise column (figure 46a) in order for the upper curvature to remain the same, the drop of water must be transmitted downward to the free water surface. In the case of the infiltration column, equation 7 represent the maximum capillary height of water (figure 46b) beyond which a positive pressure develops at the interface of the two layers as indicated by the experimental data in table 15. Because of the positive pressure the flow of moisture will continue from fine sand layer to the coarse sand layer.

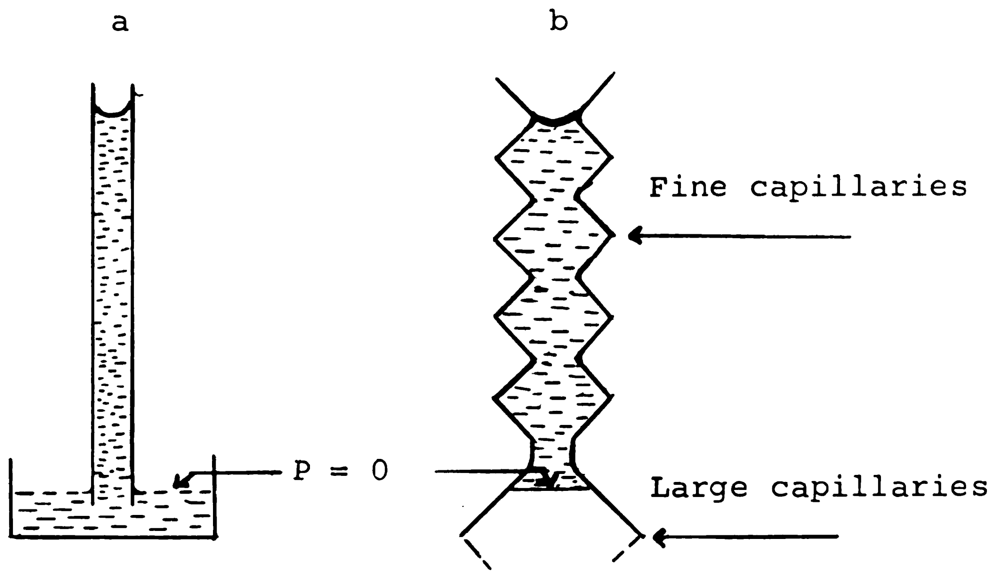


Figure 46. Capillary rise from free water table as compared to the water infiltration in stratified sand column.

Due to a change in radii of the capillaries at the interface there are two possibilities for the moisture flow in the coarse layer (1) the formed drops fall through the large pores of the coarse layer or (2) the water flow continues as a film around the large particles.

The experimental data in Figures 16 and 23 show a sharp change in the moisture tension below the coarse layer and because no pulse or fluccuation in moisture tension was detected at this region may indicate the second case was the probable mechanism of flow. However, it must be remembered that no tension data is available from the coarse stratum to verify this conclusion.

The above mechanism is based on the assumption of cylindrical capillaries. However, in the soil while the capillary phenomena exists, the capillaries are more irregular and torturous in nature. In addition to the change in size of capillaries which reduces the number of water filled channels in the coarse sand stratum through which water moves, the wetting angle of the particles is not always necessarily being zero and possible presence of entrapped air in the large pores all contribute to the restriction of moisture movement through the coarse stratum. The low conductivity in the coarse materials do not provide adequate transport, hence the positive pressure in the fine layer immediately above.

C. Rate of water application

The experimental results shown in tables 15-20 and figures 47-52 not only indicate the effect of particle size of the strata on the moisture tension distribution in a stratified sand column, but also the effect of water application rate. During infiltration the magnitude of discontinuities are a function of water application rate. With the particle size of the strata constant, the magnitude of discontinuity is decreased with a decrease in the rate of

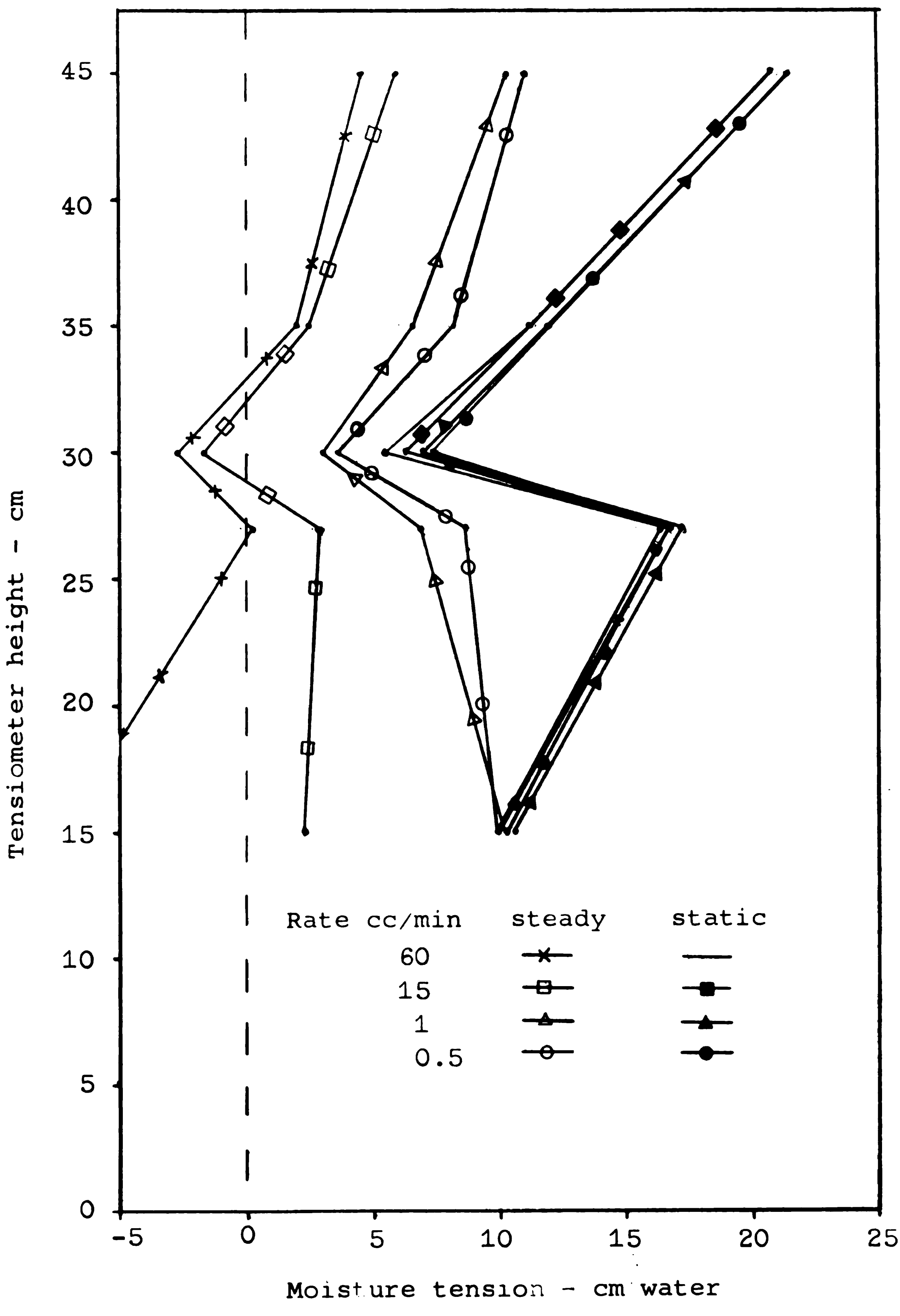


Figure 47. Moisture tension profiles for a stratified sand column (0.72/1.55/0.72 mm dia, 28 + 1 + 28 cm) under 4-rates of water application.

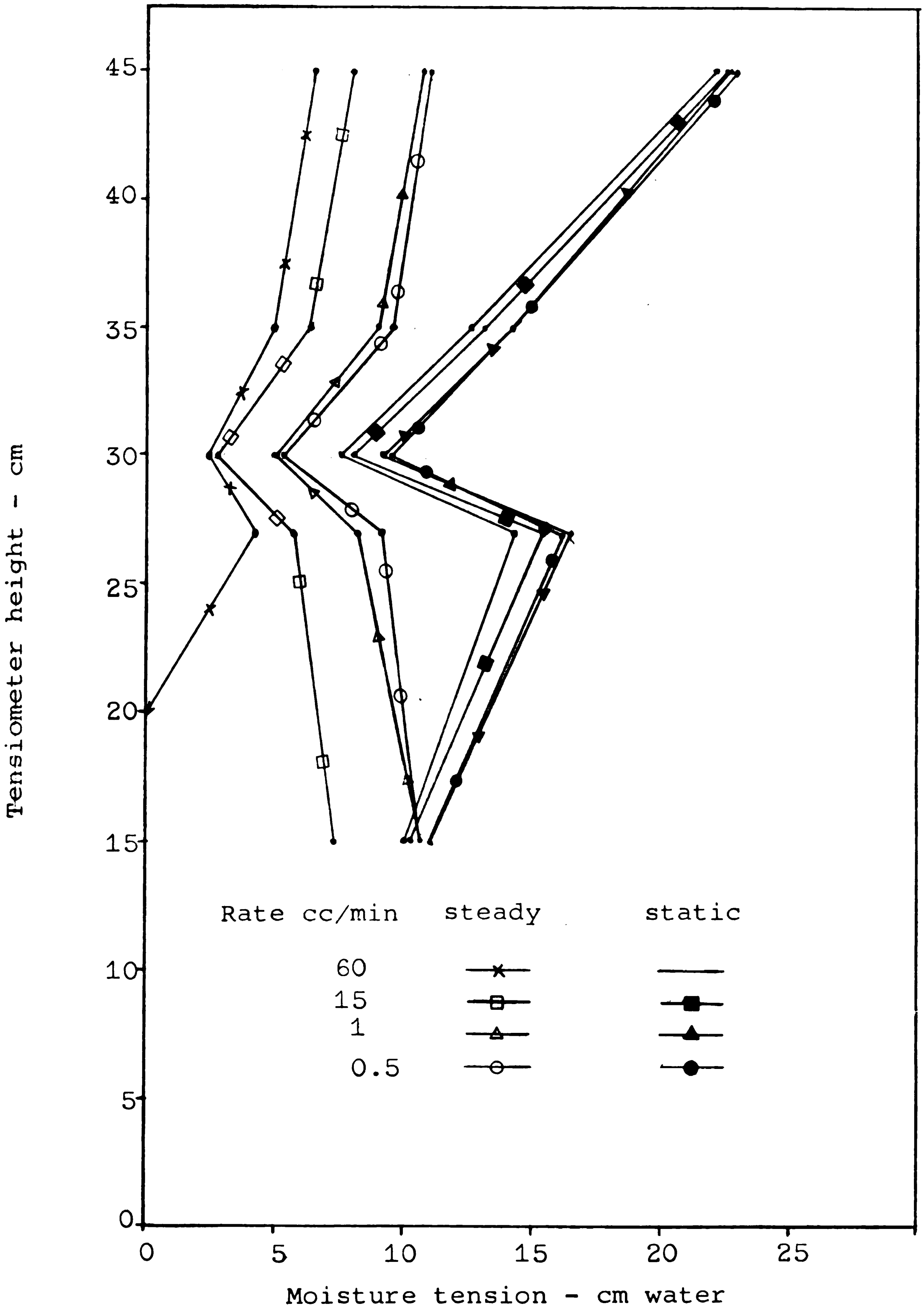


Figure 48. Moisture tension profiles for a stratified sand column (0.72/1.3/0.72 mm dia. 28 + 1 + 28 cm) under 4-rates of water application.

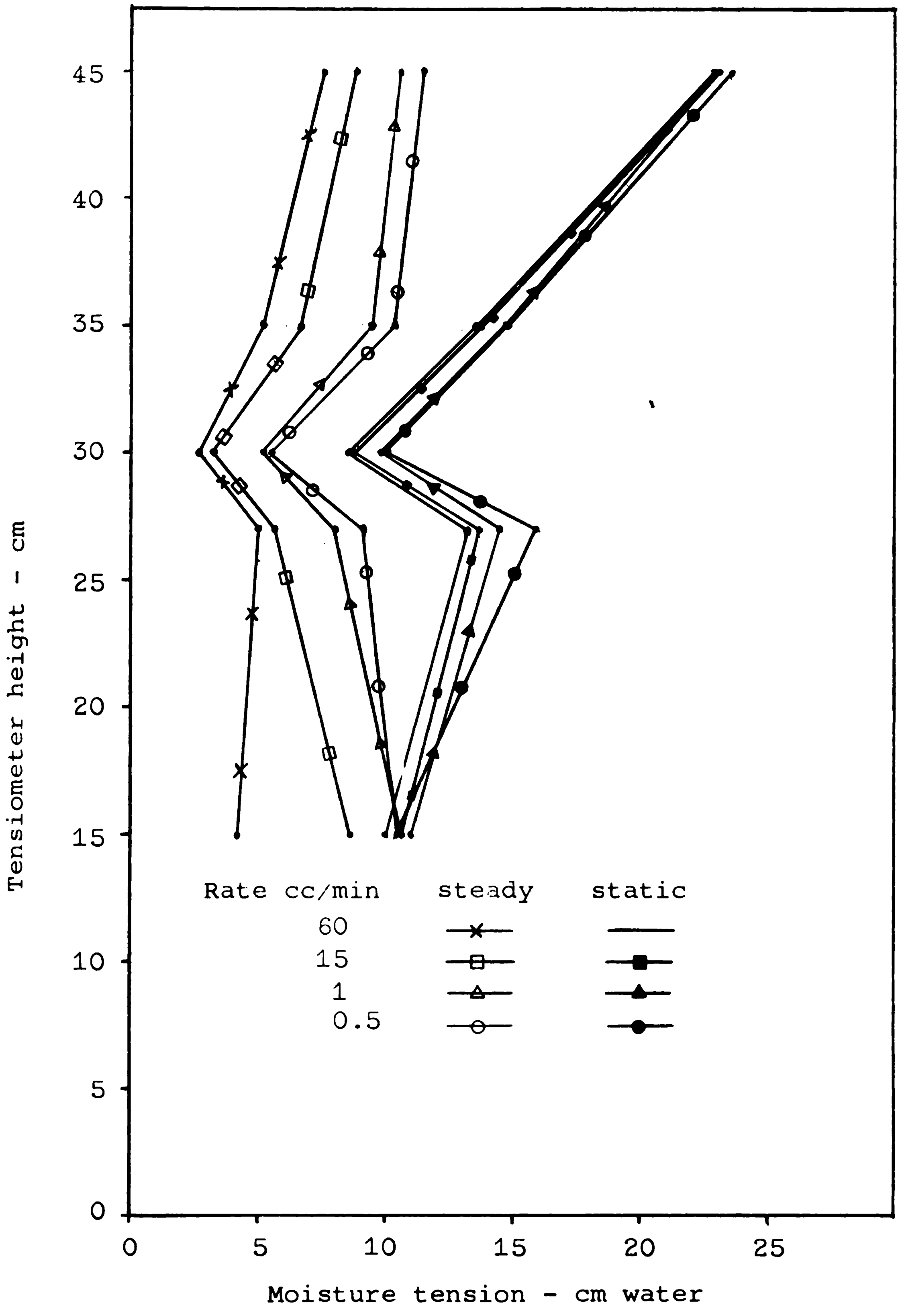


Figure 49. Moisture tension profiles for a stratified sand column (0.72/1.1/0.72 mm dia, 28 + 1 + 28 cm) under 4-rates of water application.

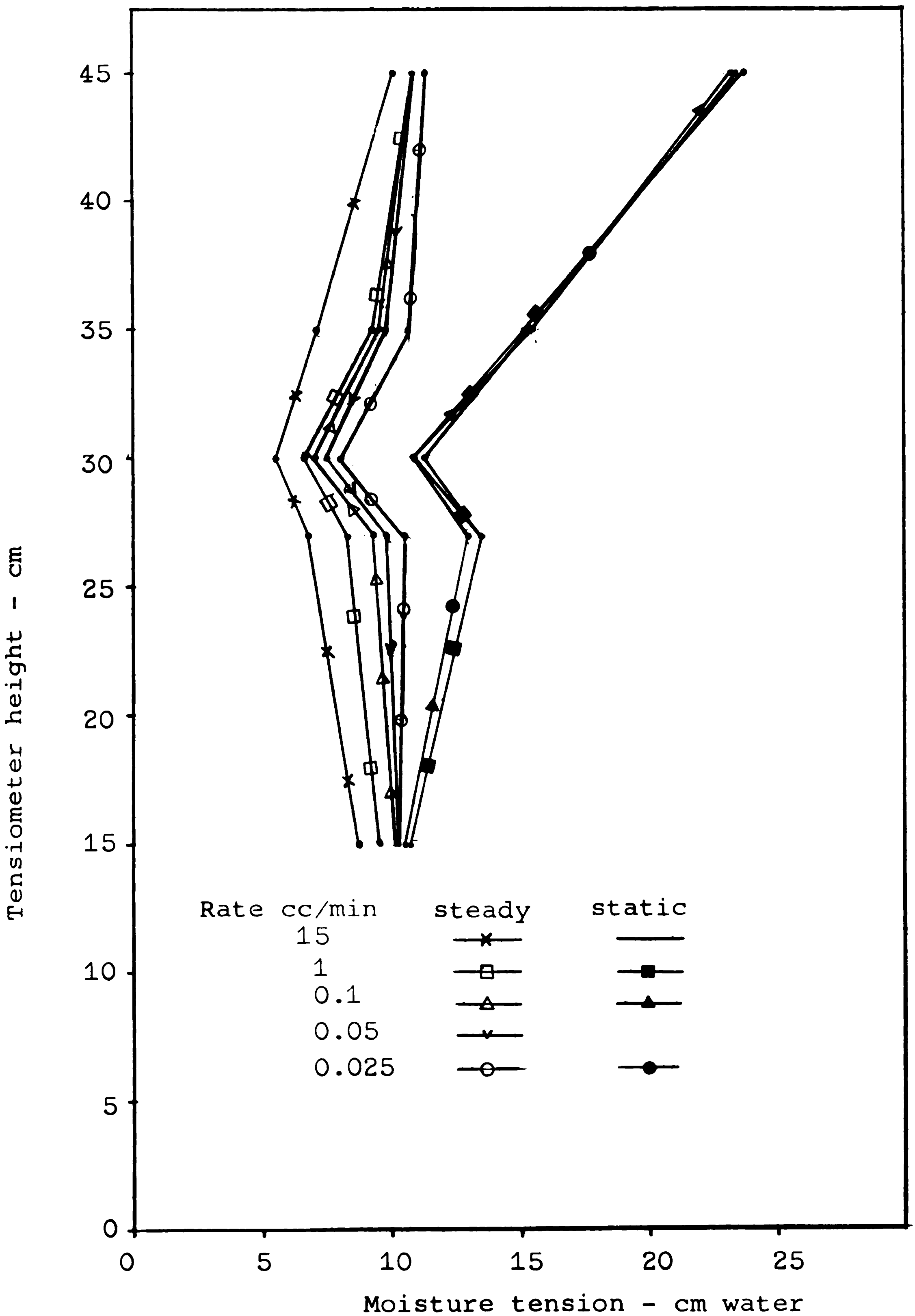


Figure 50. Moisture tension profiles for a stratified sand column (0.72/0.92/0.72 mm dia, 28 + 1 + 28 cm) under 5-rates of water application.

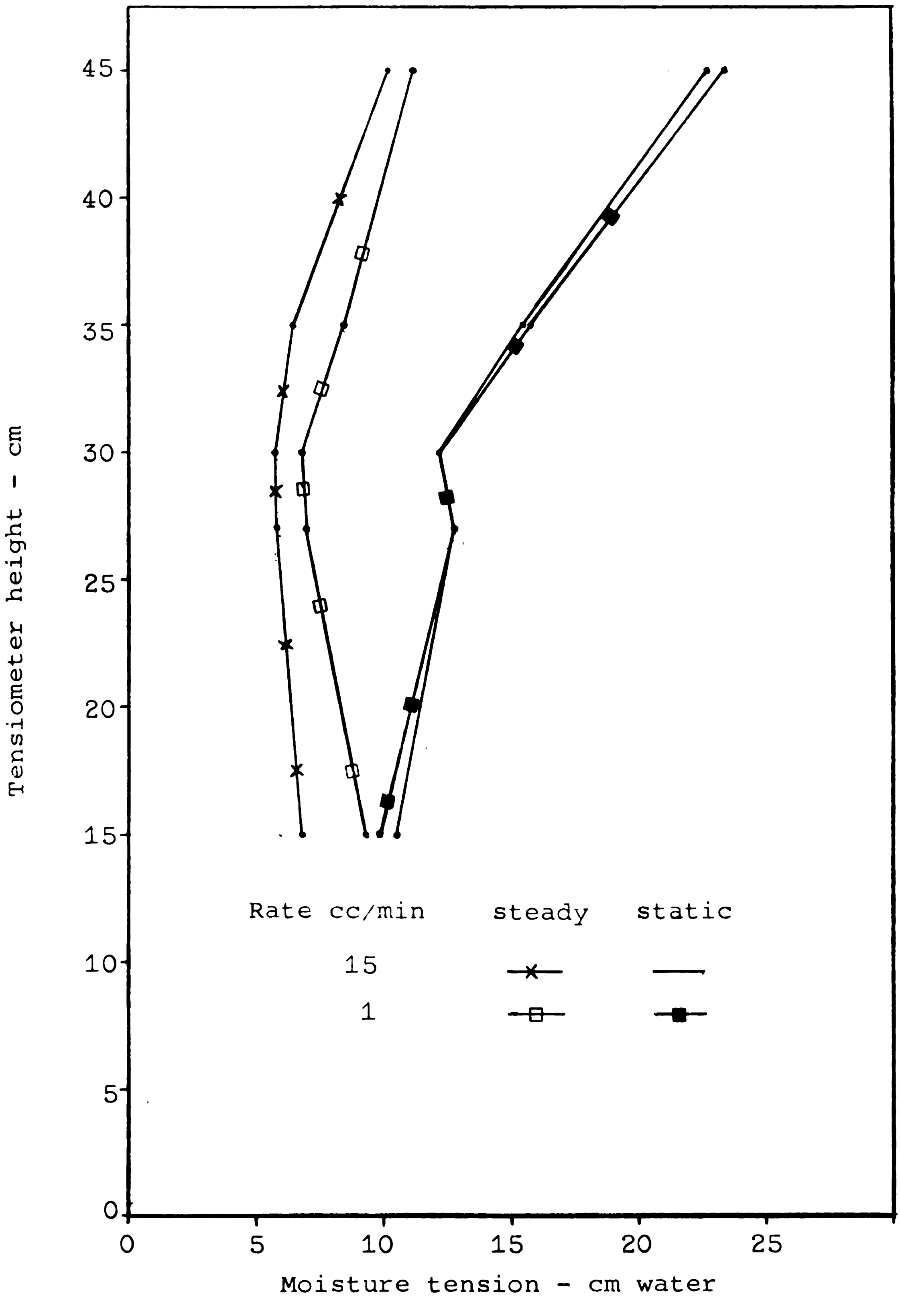


Figure 51. Moisture tension profiles for a stratified sand column (0.72/0.46/0.72 mm dia, 28 + 1 + 28 cm) under 2-rates of water application.

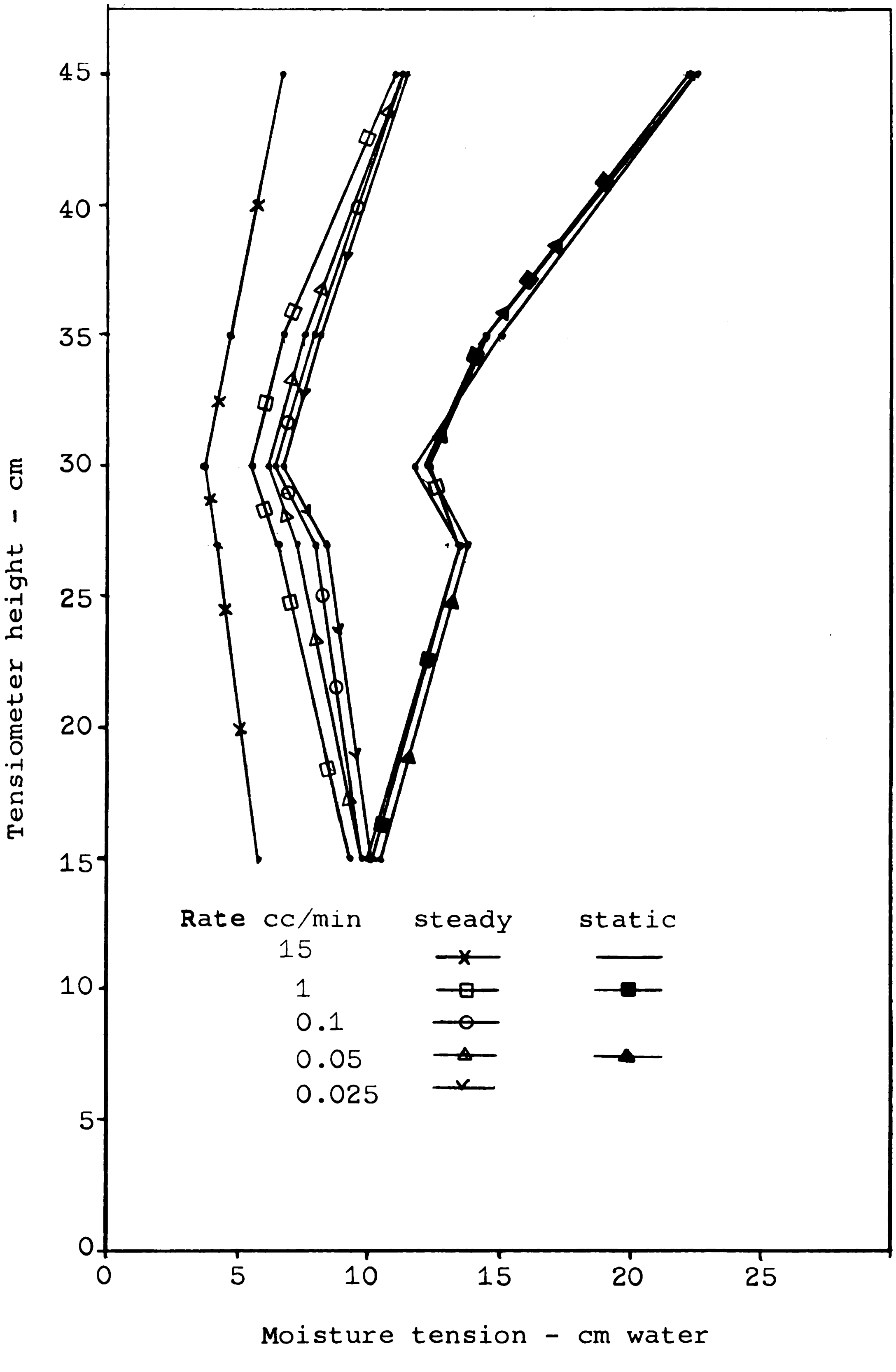


Figure 52. Moisture tension profiles for a stratified sand column (0.72/0.37/0.72 mm dia, 28 + 1 + 28 cm) under 5-rates of water application.

water application. The magnitude of discontinuity was highest with the coarsest strata and the highest rate of water application.

The results of the moisture tension distribution obtained in this study with columns of uniform sand separates are similar to one predicted and obtained by Rubin (39 and 40) and Young (47 and 48). The moisture tension values of the uniform column approach constant and equal value throughout the column with increasing time. These values remained uniform and at equilibrium as long as the rate of water application was continued at the same constant rate. During the infiltration with the lower rate of water application where the rate of application is equal or less than saturated hydraulic conductivity of the sand column, the sand at the surface becomes locally saturated then tends to drain until the second drop of water reaches the surface and wets the column to greater depth. When the wetting front becomes deep enough, the moisture distribution down the column is such as to permit the drainage of water from near-saturated material close to the surface. At this time the column at the surface is draining while that near the moisture front is wetting. The initial zone of high moisture content near the surface gradually disappears to form a moisture profile of fairly uniform moisture content and consequently a uniform moisture tension distribution behind the wetting front.

The moisture tension distribution in the stratified sand column can not be approached in the same way. This is because the sand strata by restricting the moisture movement (as a function of particle size) and formation of a perched water table above it will form two semi-independent columns. These two columns are short and a transmission zone with equal distribution of moisture tension above and below the strata does not exist. The moisture tension values in stratified columns appreach constant values throughout the column during the water flow. However, the distribution of moisture tension in stratified columns have a distinct break in its continuity above the coarse strata where the perched water table develops. This causes a delay in moisture movement in the column but as the particle size of the strata approaches the particle size of the main column the effect of the strata then decreases which results in more uniform moisture movement throughout the sand column.

D. Thickness of the strata

The thickness of the strata as well as its particle size is important to have discontinuities in the stratified sand. In order to have a discontinuity in moisture distribution in the sand column it requires the strata to have a minimum thickness to cause this phenomena. Theoretically a uniform monolayer of the strata with a uniform particle size should cause the discontinuity in moisture distribution when the difference in particle sizes of the two layers is within the limit to form a clear sharp boundary line.

It was shown in previous discussion that discontinuity is a function of coarse strata. Because the discontinuity occurs at the contact point between the two layers, the minimum thickness of the coarse strata is more important than maximum thickness.

Experimental data in table 24 and figures 37 and 53 indicate that when the thickness of the coarse layer decreased from 1 cm to 0.2 cm, which was very close to a mono-layer, the discontinuity still existed, but the magnitude of discontinuity decreased. The moisture tension distribution throughout the column was increased with a decrease in thickness of the strata. On the other hand, when the thickness of the coarse strata (in another set of experiments) increased from 2 to 4 cm as shown in table 25 and figure 54, the change in the magnitude of discontinuity was of the same order.

The thickness of the fine stratum located between two coarse layers has a different relation to moisture tension distribution in the stratified sand column. The wetting front moves downward and passes from the coarse layer to the fine stratum without restriction, but as it was suggested earlier, the coarse layer underlying the fine stratum will restrict the movement of water downward. The water accumulates above the coarse layer until the tension is low

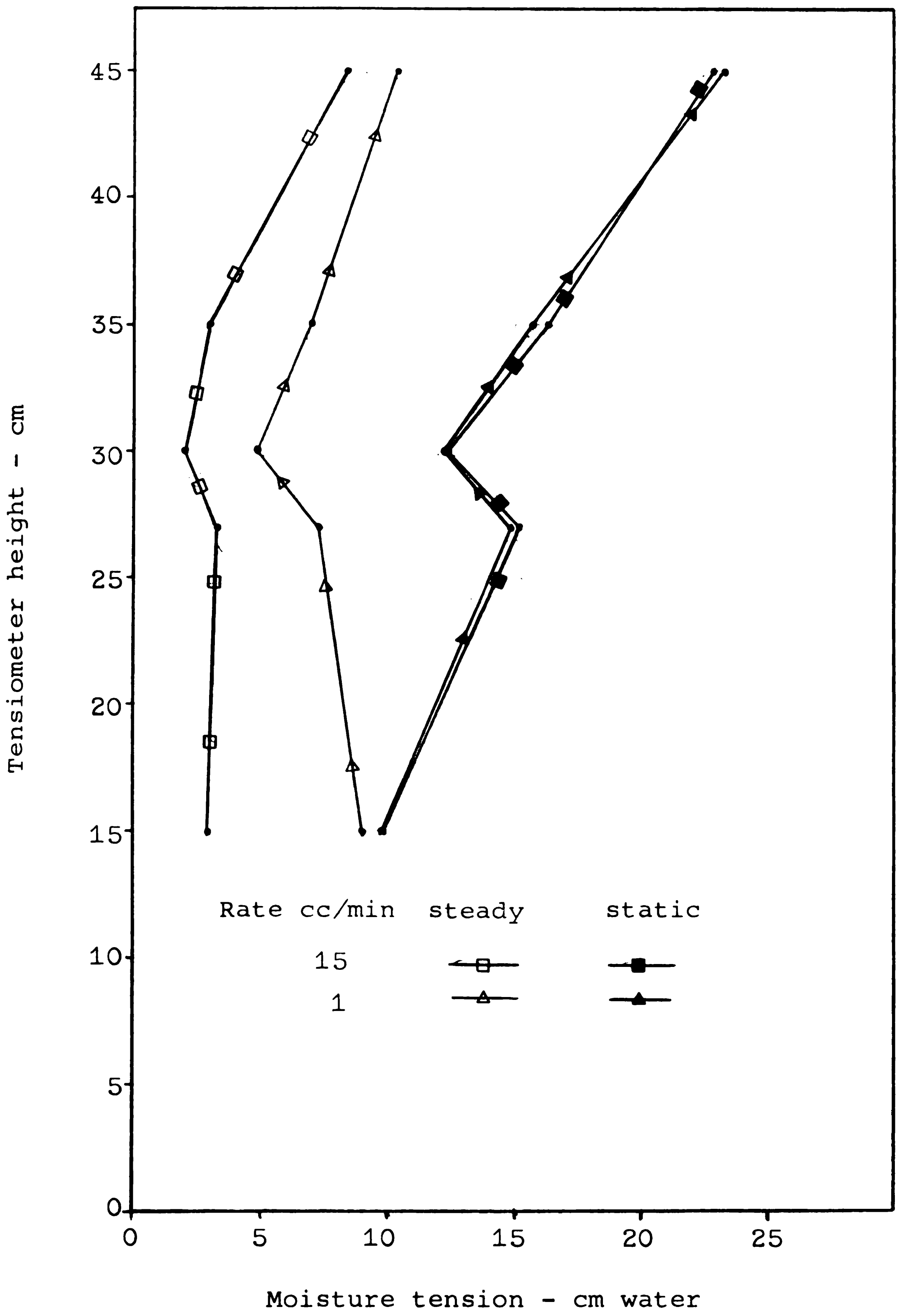


Figure 53. Moisture tension profiles for a stratified sand column (0.72/1.55/0.72 mm dia, 28.4 + 0.2 + 28.4 cm) under 2-rates of water application.

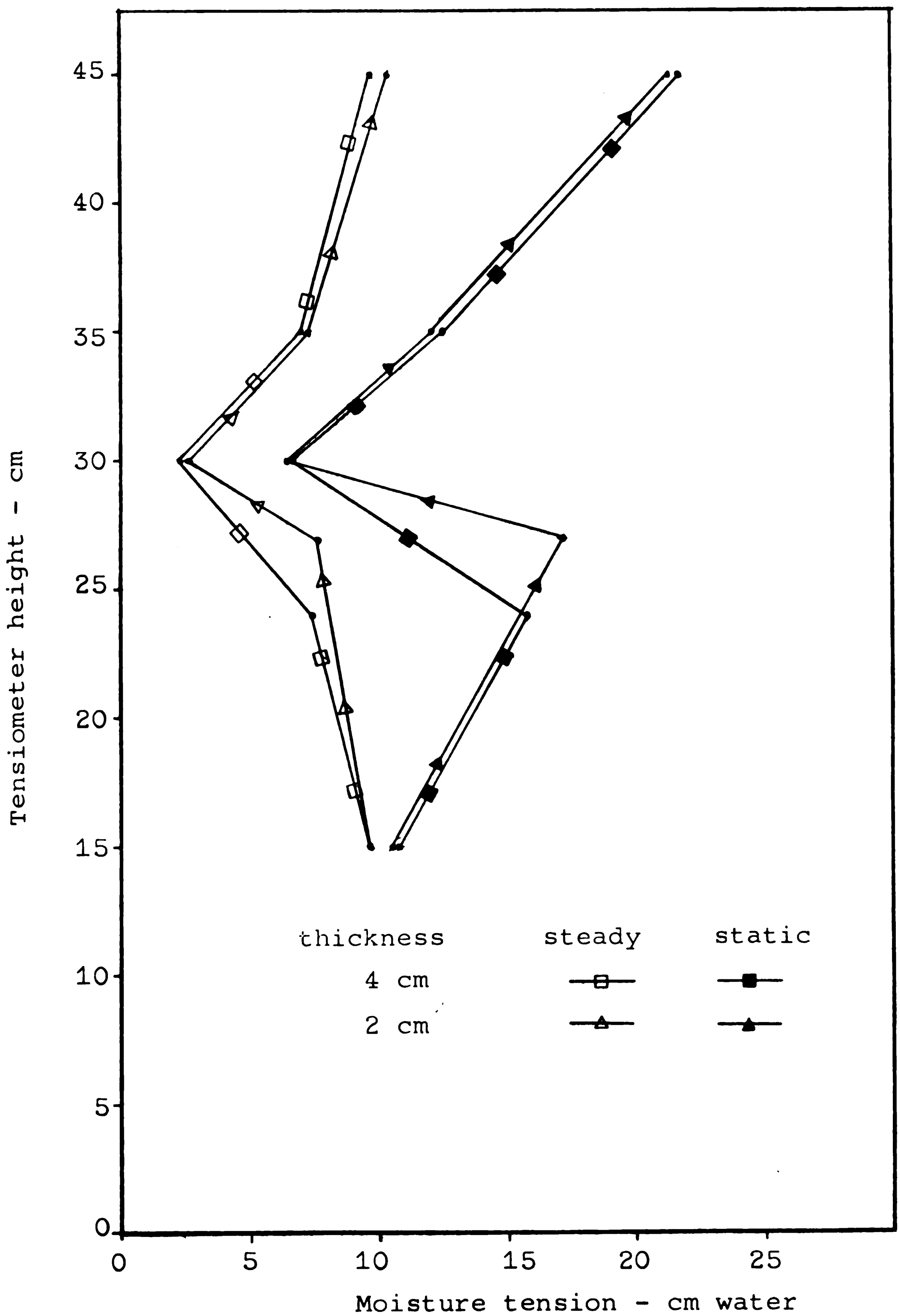


Figure 54. Moisture tension profiles for stratified sand columns (0.63/1.34/0.63) as affected by thickness of the middle stratum under one rate of water application.

enough at the boundary line to permit the movement of water downward through the coarse layer. The data in table 12 and the work of Staprens (29) suggested that in two layered systems where a coarse layer underlying a fine layer of sand the height of water accumulated above the coarse layer is equal to the difference in capillary rise of the two layers. However, it was shown from the data in table 9 that when the thickness of the bottom fine layer was increased beyond the maximum capillary rise of the overlying coarse layer, the capillary rise was stopped at the boundary line between the two layers. Consequently when the fine stratum is only a few centimeters thick the water accumulates only within the fine stratum if its height is above the capillary region of the overlying coarse layer. But as the thickness of the fine stratum increases we approach a system similar to a two-layered stratified column where a fine layer overlies a coarse layer.

It follows from the above discussion that the magnitude of the discontinuity at the boundary line of the fine stratum and underlying coarse layer may not change due to increase in thickness of the fine stratum and only the height of accumulated water will increase with a subsequent change in moisture tension values above the boundary line.

E. Practical application

The analysis and discussion of the data presented in this study has shown the relationship of soil moisture in stratified sand. The information illustrates the importance of coarse strata in stratified sands in governing the moisture distribution and the rate of water movement in these soils. The results of this study will add fundamental information which can be applied to vast areas of stratified sand material as well as similar conditions in other soils with wider ranges of textural variation.

This study contributes to the understanding of stratified sand soils in the field and explains fluctuations of moisture distribution, the increase in water holding capacity, uneven moisture movement and the slow recharge of the water to the water table. The presence of a coarse layer overlying a fine sand layer prevented continuation of capillary rise in these soils, even in the capillary region of soil. This will restrict the upward movement of water and could decrease evaporation. This advantage of decreasing evaporation from soil surface could be offset by the decrease in the water supply from the water table which is essential for plant growth. But at the same time, the presence of the coarse layer in the profile will result in accumulation of water above the coarse layer from applied water whether rain, snow or irrigation. This increases the amount of water available for the plant growth.

Presence of stratified sand soils, especially when the layers are repeated at shorter intervals in the profile, will create in some cases a drainage problem in these soils not only with respect to the depth of the tile drains, but, also could cause a problem of aeration as water accumulated throughout the profile.

Restriction of upward movement of capillary water by the coarse layer will help in preventing the salt accumulation at soil surface if these salts were washed down the profile under the coarse layer.

VI. SUMMARY AND CONCLUSIONS

Effect of strativication in sands on moisture movement and moisture distribution were studied in relation to the texture of the strata and thickness of the strata. Soil moisture content and moisture tension measurements under various rates of water application were used.

The results of these studies can be summarized as follows:

1. Discontinuities do exist in stratified sand material when a coarse layer underlays a fine layer as well as the reverse, which is commonly expected.

2. Discontinuities are a function of particle size of the strata. The greater the difference between the particle size of the layers, the greater the magnitude of the discontinuity in the stratified sand columns. This is evidenced by (a) movement and distribution of moisture with time during infiltration and (b) amount of water accumulated above the strata.

3. Magnitude of discontinuities are independent of the stratum thickness once a minimum thickness to establish the discontinuity is reached. This minimum thickness in an ideal, well differentiated stratum is probably one particle thick.

4. During infiltration the magnitude of discontinuities is a function of water application rate.

5. Although the moisture tension required to drain a soil depends on its particle size, in stratified soils the size of particles in a coarse layer can govern the drainage of the entire profile.

The discontinuity phenomena in coarse materials can be explained in the following way:

The wetting front moves downward in the upper fine sand until it contacts the coarse sand strata. At the interface of the two layers, a change in pore size occurs where the small pores contact the large pores of the coarse stratum. Because the coarse stratum is incapable of conducting water at a high tension at the point of contact, water cannot move into this layer. As a result, the wetting front advance stops. In order for the wetting front to move further downward, the moisture tension at that point must decrease by water accumulation until it is low enough to allow water to pass into the pores in the coarse strata.

When water finally moves through a coarse sand stratum and consequently into the fine sand below, the advance of the wetting front continues as long as the water application continues at the surface.

BIBLIOGRAPHY

1. Alway, F.J. and McDale, G.R. Relation of water retaining capacity of a soil to its hygroscopic coefficient. Jr. Agr. Research, 9:27-71, 1917.

2. Bianchi, W.C. Measuring soil moisture tension changes device transforms soil and moisture tension into electrical resistance change. Agr. Eng. 43:398-399, 404, 1962.

3. Baver, L.D. Soil physics, 3rd edition, John Wiley and Sons, Inc., New York, 1959.

4. Bodman, G.B. and Colman E.A. Moisture and energy conditions during downward entry of water into soils. Soil sci. Soc. Am. Proc. 8:116-122, 1944.

5. Bol'shakov, A.F. Effect of two layered alluvium on water regime of thick Chernozem. Soviet Soil Sci. 6:783-790, 1959.

6. Colman, E.A. and Bodman, G.M. Moisture and energy conditions during downward entry of water into moist and layered soils. Soil Sci. Soc. Am. Proc. 9:3-11, 1945.

7. Dougrameji, J.S. The relation of particle size distribution to available moisture and capillary rise of water. Special problem, Michigan State University, 1960.

8. ________. Capillary rise in uniform and layered sand separates. Unpublished data, Michigan State University, 1962.

9. Eagleman, J.R. and Jamison, V.C. Soil layering and compaction effects on unsaturated moisture movement. Soil Sci. Soc. Am. Proce. 26:519-522, 1962.

10. Felitsiant, I.N. Capillary movement of moisture in stratified soils. Soviet Soil Sci. 3:282-292, 1959.

11. ________. Capillary movement and accumulation of moisture in stratified soils. Soviet Soil Sci. 10: 1099-1107, 1961.

12. Ferguson, M. Soil modification. The Golf Course Reporter. 25:4-7, 1957.

13. Fireman, M. Permeability measurements on disturbed soil samples. Soil Sci. 58:337-354, 1944.

14. Franzmeier, D.P., Whiteside, E.P. and Erickson, A.E. Relationship of texture classes of fine earth to readily available water. 7th Intern. Cong. of Soil Science, Madison, Wisc. 1:354-363, 1960.

15. Glasstone, S. and Lewis, D. Elements of physical chemistry, 3rd edition, D. Van Nostrand Company, Inc., 1960.

16. Hanks, R.J. and Bowers, S.A. Numerical solution of the moisture flow equation for infiltration into layered soils. Soil Sci. Soc. Am Proc. 26:530-534, 1962.

17. Harris, F.S. and Turpin, H.W. Movement and distribution of moisture in soil. J. Agr. Research. 10:113-155, 1917.

18. Holmes, J.L. Factors in building a green. The Golf Course Reporter, March-April, 39-41, 1959.

19. Huggins, L.F. Microdifferential pressure transducer. Agr. Eng. 43:529-531, 1962.

20. Klute, A. and Peters, D.B. Recording tensiometer with a short response time. Soil Sci. Soc. Am. Proc. 26: 87-88, 1962.

21. Leamer, R.W. and Shaw, B. A simple apparatus for measureing non-capillary porosity, on an extensive scale. J. Am. Soc. Agron. 33:1003-1008, 1941.

22. Lebedeff, A.F. The movement of ground and soil water. 1st Intern. Cong. of Soil Science, Washington, D.C. 1:459-494, 1927.

23. Leonard, R.A. and Low, P.F. A self-adjusting, null-point tensiometer. Soil Sci. Soc. Am. Proc. 26:123-125, 1962.

24. Loughridge, R.H. Investigations in soil physics; the capillary rise of water in soils. Calif. Agr. Exp. Sta. Ann. Rept. 91-100, 1894.

25. Luthin, J.N. Percolation of water through saturated layered soil separates. M.S. thesis, Michigan State University, 1947.

26. Mamanina, L. The effect of insulating interlayers on the height of capillary rise of water in heavy loams. Pedology 2-3;101-105, 1944.

27. McLaughlin, W.W. Capillary movement of soil moisture, U.S. Dept. Agr. Tech. Bull. 835, 1920.

28. ________. The capillary distribution of moisture in soil columns of small cross section. U.S. Dept. Agr. Tech. Bull. 1221, 1924.

29. Miller, D.E. Effect of profile stratification and other factors on water infiltration. Ph.D. thesis, State College of Washington, 1959.

30. ________. Lateral moisture flow as a source of error in moisture retention studies. Soil Sci. Soc. Am. Proc. 27:617-717, 1963.

31. ________. Layered soil. U.S. Dept. Agr. Research Bull. Jan., 1965.

32. ________, and Bunger, Wm. C. Moisture retention by soil with coarse layers in the profile. Soil Sci. Soc. Am. Proc. 27:586-589, 1963.

33. ________, and Gardner, W.H. Water infiltration into stratified soil. Soil Sci. Soc. Am. Proc. 26:115-119, 1962.

34. Miller, R.D. A technique for measuring soil moisture tension in rapidly changing systems. Soil Sci. 72:291-301, 1951.

35. Moore, W.J. Physical Chemistry 3rd edition, Prentice-Hall, Inc., 1964.

36. Moote, R.F. Green construction. The Golf Course Reporter. 42-47, 1961.

37. Nelson, W.R. and Baver, L.D. Movement of water through soils in relation to the nature of the pores. Soil Sci. Soc. Am. Proc. 5:69-76, 1940.

38. Richards, L.A. Methods of measuring soil moisture tension. Soil Sci. 68:95-112, 1949.

39. Rubin, J. Soil water relations during rain infiltration: I. Theory. Soil Sci. Soc. Am. Proc. 27:246-251, 1963.

40. Rubin, J., Steinhardt, S. and Reiniger, P. Soil water relations during rain infiltration: II. Moisture content profiles during rains of low intensities. Soil Sci. Soc. Am. Proc. 28:1-5, 1964.

41. Scott, V.H. and Corey, A.T. Pressured distribution during steady flow in unsaturated sand. Soil Sci. Soc. Am. Proc. 25:270-274, 1961.

42. Spangler, M.G. Soil engineering. International Textbook Company, Scranton, 1951.

43. Staprens, V. Ya. Translational migration of capillary-suspended moisture in sandy soils. Soviet Soil Sci. 4:355-359, 1961.

44. The USGA Green Section Staff. Specification for a method of putting green construction. USGA J. Turf Manage. 1-7, 1960.

45. Thiel, T.J., Fouss, J.L. and Leach, A.P. Electrical water pressure transducers for field and laboratory. Soil Sci. Soc. Am. Proc. 27:601-602, 1963.

46. Willis, W.O. Evaporation from layered soil in the presence of water table. Soil Sci. Soc. Am. Proc. 24: 239-242, 1960.

47. Youngs, E.G. Moisture profiles during vertical infiltration. Soil. Sci. 84:283-290, 1957.

48. ________. The hysteresis effect in soil moisture studies. 7th Intern. Cong. of Soil Science, Madison, Wisconsin, I:107-112, 1960.

APPENDIX

Table 26. Percent moisture by weight at various tensions in cores consisting of two layers of sand separates.

Particle size ratio[1]	Moisture tension-cm water[2]						
	sat.	0	5	10	15	20	25
	Percent moisture by weight						
$\frac{2.84}{0.23}$	31.6	21.0	18.4	17.7	17.4	17.0	16.9
$\frac{2.2}{0.23}$	31.7	22.3	18.4	17.7	17.4	17.0	16.6
$\frac{1.34}{0.23}$	32.6	27.5	18.8	17.9	17.5	17.1	16.8
$\frac{0.8}{0.23}$	32.3	30.9	22.9	18.9	18.1	17.5	17.2
$\frac{0.63}{0.23}$	33.6	32.4	31.5	22.2	19.1	17.9	17.4
$\frac{0.38}{0.23}$	34.3	33.0	32.4	31.5	22.4	19.0	18.3
$\frac{0.23}{0.23}$	36.0	34.7	34.3	34.0	33.6	33.3	32.6

[1]The ratio of average particle size of upper layer to average particle size of bottom layer.

[2]Tension values at the bottom of the core, add 3.5 cm to get an average tension value.

[3]Ratio of percent moisture in upper layer to bottom layer at 60 cm tension.

30	35	40	45	50	-55	60	distribution ratio[3]
15.5	7.4	4.5	3.1	2.6	2.3	2.1	0.0
15.3	7.5	4.4	3.1	2.6	2.3	2.1	0.1
15.6	7.5	4.5	3.2	2.6	2.3	2.1	0.1
14.5	7.1	4.3	3.1	2.6	2.3	2.1	0.1
15.1	7.5	4.5	3.2	2.7	2.3	2.1	0.1
15.8	7.8	4.9	3.4	2.9	2.5	2.2	0.2
21.9	11.4	7.2	5.0	4.2	3.6	3.3	1.0

Table 27. Percent moisture by weight at various tensions in cores consisting of two layers of sand separates.

Particle size ratio	Moisture tension-cm water						
	sat.	0	5	10	15	20	25
	Percent moisture by weight						
$\frac{2.84}{0.38}$	29.7	19.8	16.2	15.5	15.2	14.7	14.0
$\frac{2.2}{0.38}$	29.9	22.3	16.3	15.6	15.4	14.7	13.5
$\frac{1.34}{0.38}$	30.4	28.0	17.0	16.2	15.8	15.2	13.9
$\frac{0.8}{0.38}$	30.3	29.4	20.7	17.1	16.1	15.3	14.2
$\frac{0.63}{0.38}$	30.7	30.2	29.3	23.6	18.0	16.4	14.5
$\frac{0.38}{0.38}$	32.3	31.6	30.9	30.3	28.4	19.3	14.8
$\frac{0.23}{0.38}$	32.7	32.2	31.8	31.6	31.3	31.2	30.6

							distribution ratio
30	35	40	45	50	55	60	
11.9	10.2	8.6	7.4	6.2	4.9	3.8	0.1
11.0	9.5	8.1	6.8	5.7	4.6	3.8	0.1
11.3	9.4	8.0	7.0	5.9	4.7	3.9	0.1
12.3	10.5	8.9	7.7	6.5	5.1	4.1	0.2
11.4	9.8	8.4	7.5	6.4	5.2	4.3	0.2
11.4	9.5	8.1	6.9	5.7	4.4	3.5	1.0
27.8	26.1	24.8	23.9	22.8	21.7	20.9	4.2

Table 28. Percent moisture by weight at various tensions in cores consisting of two layers of sand separates.

Particle size ratio	Moisture tension-cm water						
	sat.	0	5	10	15	20	25
	Percent moisture by weight						
2.84/0.63	29.3	17.5	15.3	13.4	3.9	2.3	1.8
2.2/0.63	29.6	18.7	15.6	13.5	3.8	2.3	1.8
1.34/0.63	29.6	23.9	16	13.9	4.1	2.4	1.9
0.8/0.63	29.8	28.4	19.7	14.5	4.3	2.6	2.1
0.63/0.63	30.8	29.7	28.7	16.6	5.3	3.2	2.6
0.38/0.63	30.4	29.3	28.9	27.2	8.8	4.6	3.7
0.23/0.63	32.7	31.6	31.1	30.5	20.6	19.0	18.3

	30	35	40	45	50	55	60	distribution ratio
	1.5	1.2	1.1	1.0	0.8	0.7	0.7	0.2
	1.5	1.3	1.1	0.9	0.8	0.7	0.7	0.6
	1.6	1.4	1.2	1.0	0.9	0.8	0.7	0.7
	1.8	1.5	1.3	1.1	0.9	0.8	0.7	0.6
	2.2	1.9	1.6	1.3	1.0	0.9	0.8	1.0
	3.2	2.7	2.3	2.0	1.7	1.5	1.3	1.2
	17.8	17.4	16.8	16.5	16.0	15.6	15.2	23.6

Table 29. Percent moisture by weight at various tensions in cores consisting of two layers of sand separates.

Particle size ratio	Moisture tension-cm water						
	sat.	0	5	10	15	20	25
	Percent moisture by weight						
$\frac{2.84}{0.8}$	28.7	17.0	14.1	4.0	2.3	1.7	1.4
$\frac{2.2}{0.8}$	28.4	18.4	14.2	4.0	2.4	1.7	1.4
$\frac{1.34}{0.8}$	29.2	23.2	14.6	4.1	2.5	1.7	1.4
$\frac{0.8}{0.8}$	28.7	27.1	18.6	5.4	3.1	2.2	1.7
$\frac{0.63}{0.8}$	29.2	28.1	27.2	8.7	4.2	2.9	2.4
$\frac{0.28}{0.8}$	29.8	29.0	28.3	18.1	8.1	6.0	4.8
$\frac{0.23}{0.8}$	30.5	29.5	29.2	28.9	28.9	18.2	17.7

30	35	40	45	50	55	60	distribution ratio
1.1	1.0	0.8	0.7	0.6	0.6	0.6	0.0
1.1	1.0	0.9	0.7	0.7	0.7	0.6	0.0
1.1	1.0	0.9	0.7	0.7	0.7	0.6	0.0
1.3	1.2	1.0	0.8	0.7	0.7	0.6	0.6
1.8	1.5	1.2	0.9	0.8	0.7	0.6	0.0
3.8	3.3	2.7	2.2	1.9	1.7	1.3	2.9
17.2	16.9	16.5	16	15.9	15.6	15.3	37.0

Table 30. Percent moisture by weight at various tensions in cores consisting of two layers of sand separates.

Particle size ratio	Moisture tension-cm water						
	sat.	0	5	10	15	20	25
	Percent moisture by weight						
1.34/1.34	28.8	22.1	6.8	2.5	1.7	1.2	0.9
0.8/1.34	27.7	26.8	12.8	4.1	2.8	2.3	1.7
0.63/1.34	28.1	26.9	26.6	13.6	11.8	10.9	9.9
0.28/1.34	28.2	26.9	26.7	26.3	15.2	14.5	13.6
0.28/1.34	29.9	28.8	28.5	28.2	28.0	27.7	18.1

							distribution ratio
30	35	40	45	50	55	60	
0.8	0.7	0.6	0.6	0.6	0.5	0.5	1.0
1.2	1.0	0.7	0.7	0.7	0.6	0.5	0.0
9.0	8.5	7.9	7.3	6.6	6.1	5.7	8.3
12.7	12.2	11.7	11.4	10.8	10.6	10.3	26.3
17.5	17.3	16.9	16.8	16.3	16.2	16.1	87.7

Table 31. Percent moisture by weight at various tensions in cores consisting of two layers of sand separates.

Particle size ratio	Moisture tension-cm water						
	sat.	0	5	10	15	20	25
	Percent moisture by weight						
$\frac{2.84}{2.2}$	29.9	16.2	3.3	2.0	1.6	1.2	1.0
$\frac{2.2}{2.2}$	29.3	21.1	3.5	2.3	1.7	1.4	1.2
$\frac{1.34}{2.2}$	30.1	24.6	3.7	2.5	2.0	1.6	1.4
$\frac{0.8}{2.2}$	28.6	27.4	8.1	5.4	4.2	3.6	3.4
$\frac{0.63}{2.2}$	27.7	26.4	25.5	13.5	12.2	11.4	10.7
$\frac{0.28}{2.2}$	27.5	26.2	25.6	25.1	15.0	14.5	14.1
$\frac{0.23}{2.2}$	28.2	27.0	26.5	26.2	25.7	24.7	16.6

	30	35	40	45	50	55	60	distribution ratio
	0.8	0.7	0.7	0.6	0.5	0.4	0.4	0.0
	0.9	0.9	0.7	0.7	0.6	0.6	0.5	1.0
	1.1	1.0	0.9	0.9	0.8	0.6	0.6	0.0
	2.6	2.4	2.3	2.1	2.0	1.9	1.8	3.6
	9.7	9.1	8.8	8.7	8.2	7.9	7.6	15.2
	13.5	12.8	12.4	11.9	11.6	11.4	11.1	22.2
	15.9	15.6	14.9	14.7	14.5	14.3	14.3	28.6