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INVESTIGATION OF
CAPILLARY PRESSURE CHARACTERISTICS
OF UNCONSOLIDATED SANDS
BY RESISTIVITY MEASUREMENTS

by

Ibrahim Palaz

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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Geophysics).

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ABSTRACT

Laboratory resistivity measurements were carried out for 3 different grain sizes of an unconsolidated Ottawa sand to determine the m (cementation factor) and n (saturation exponent) values for each pack and the water saturation (S_w) distribution along each sand column. Porosity and permeability of the sands were found with conventional methods. Resistivity readings were taken every cm of the 112 cm long column when it was 100% brine saturated (R_o). Readings were also taken after 1, 2, 3 and 7 days as the water distribution in the column approached equilibrium (R_t). Values of m and n were calculated using the porosity, formation factor and the total volume of water in the pore space measured previously. Later, water saturation versus height (S_w-h) and capillary pressure versus water saturation (P_c-S_w) equilibrium curves were determined. A similar experiment was also carried out for a column of sand which had different grain size layers. The S_w-h relation curves were determined 1, 2, 3 and 7 days later. Correlation of S_w-h and P_c-S_w relationships for the homogeneous sand column with the layered sand column showed that capillary pressure in the layered column was a function of the height above the free water table.

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Presence of a 100% water saturated sand below or above adjacent sand did not alter the capillary pressure curve within the adjacent sand.

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GLOSSARY OF TERMS USED

- ϕ Porosity-fractional part or percentage of rock bulk volume in pores.
- F Formation factor-ratio of bulk rock resistivity when 100% water saturated to resistivity of water in pores, i.e., $F = R_o/R_w$
- m Cementation exponent-exponent in equation $F = \phi^{-m}$.
- n Saturation exponent-exponent in equation $S_w^{-n} = R_t/FR_w$.
- R_w Water resistivity-resistivity of water in pores of a rock (ohm-m).
- R_t True resistivity-bulk rock resistivity (ohm-m).
- R_o Resistivity of rock when it is 100% saturated with water of resistivity R_w ($R_o = FR_w = \phi^{-m}R_w$).
- S_w Water saturation-fractional part or percentage of pore space occupied by water. $S_w^{-n} = R_t/R_o = R_t/FR_w$
- P_c Capillary pressure- $P_c = g \cdot h \cdot (\rho_{f1} - \rho_{f2})$.
- h Height (cm).
- k Single fluid permeability-permeability of rock to fluid when that fluid alone occupies the pore space (Darcy).
- W_w Weight of sample when it is 100% water saturated (gr).
- W_d Weight of sample when it is dry (gr).
- ρ_m Grain density-density of grain or matrix material (gr/ml).
- L Length (cm).
- g Acceleration due to gravity (cm/sec^2).
- ρ_f Density of fluid (gr/ml).

μ	Viscosity (centipoise).
A	Cross sectional area (cm^2).
R	Resistance $R = V/I$ (ohm).
I	Current (ampere).
V	Voltage (volt).
G	Geometrical factor.
ρ	Resistivity $\rho = G \cdot \Delta / I$ (ohm-m).
θ	Contact angle.
$R_1,$ R_2	Radii of curvatures (cm).
ρ_w	Density of water (gr/ml).
ρ_a	Density of air (gr/ml).
β	Surface tension.
V_t	Total volume of water, ml.

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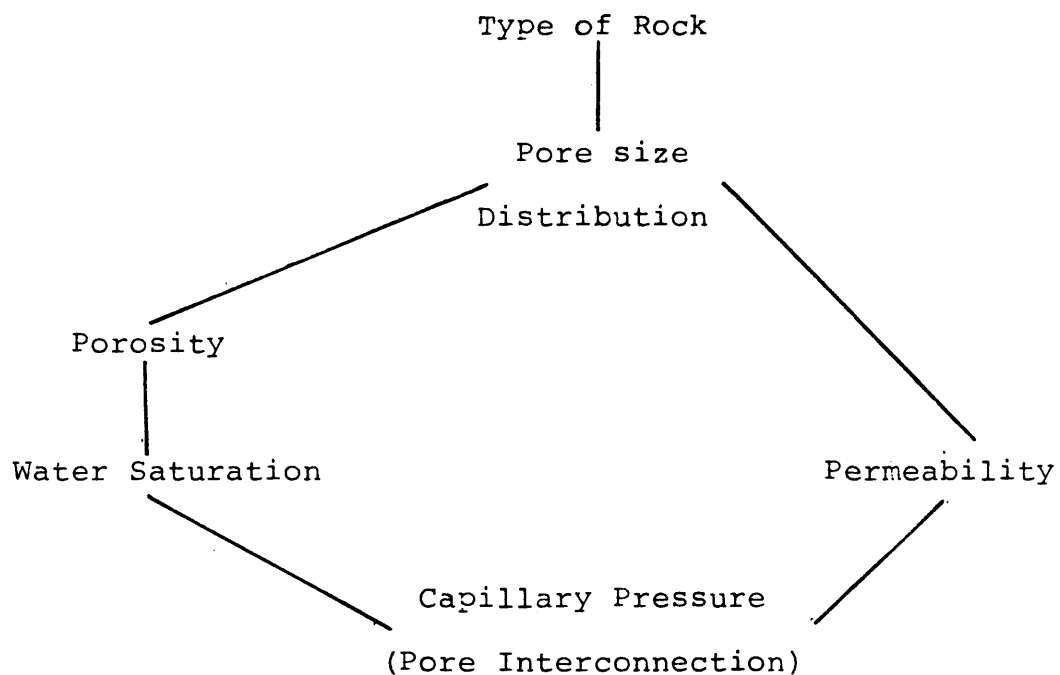
I wish to thank the people from the Halliburton Ft. Lupton office for supplying the Ottawa sands for the experiment. Without them the results would not have been nearly as clear.

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INTRODUCTION

The relationships between the basic rock pore properties may be indicated as follows:



The connecting lines are meant to portray the fact that a specific sample of rock will have pore size distribution which will produce a particular family of capillary pressure curves.

Thesis Objective

The objective of this thesis is to determine the interrelations among the rock properties of some synthetic unconsolidated sands.

Approach of Study

This study consists of four parts. The first part is a review of some rock properties. This part reviews the basic theory of the relations among the rock properties. The second part explains the laboratory measurements, their reliability and quality control. The third part presents the data collected and the relations among them. The fourth part is the conclusion of the work and a brief discussion of its implications.

REVIEW OF THE THEORY OF THE RELATIONS
AMONG ROCK PROPERTIES

Factors Controlling the Porosity
of Unconsolidated Natural Deposits

The following factors control the porosity of unconsolidated natural deposits;

- A - Absolute sizes of grains
- B - Non-uniformity in sizes of grains
- C - Proportions of various sizes of grains
- D - Shape of grains

A - Effect of Absolute Grain Size

The effect of absolute grain size on porosity should be considered with the combination of many other factors. Direct and reliable comparisons between the porosity conditions existing in assemblages of uniform spheres and those in natural deposit cannot ordinarily be made (1).

B - Effect of Non-uniformity of Grain Size

Whether the grain size is uniform or non-uniform is of fundamental importance with respect to porosity. The highest porosity is commonly obtained when the grains

are all of the same size. To such an assemblage, the addition of grains of either a larger or a smaller size tends to lower the porosity. This generalization is made clear by consideration of assemblages containing spheres of two sizes. As the large spheres and small spheres become increasingly different in diameter, the relative value of the first influence mounts and that of the second declines; therefore porosity progressively decreases (1).

C - Proportions of Various Grain Sizes

When two sizes of spheres are mixed, the smaller size dominates the general structure of the assemblage as long as the proportion of its spheres is sufficiently great to keep most of the large spheres separated from one another. Under such conditions, small spheres and their own voids play the role of a matrix. In this circumstance there is a fairly uniform drop in the porosity of the combination as the proportion of large spheres grows (1).

D - Effect of Shape of Grains

The shape of grains in sediments is probably never truly spherical, but varies within limits, according to the character of the original mineral or material, the shape of the original fragments, the degree of wear that the grains have undergone, and the method of transportation and deposition.

Irregularities in shape should result in a larger possible range in porosity, as irregular forms may theoretically be packed either more tightly or more loosely than spheres.

It is difficult to determine the effect of grain shape on porosity because of the difficulty in obtaining angular particles of the same size. Screening is an unsatisfactory method of separation, especially for particles that have a similar cross section but vary in length. Therefore, determination of the effect of grain shape on porosity is always attended by a second independent variable, that of grain size (2).

Formation Resistivity Factor (F) and Formation Resistivity (R_t)

The Formation Resistivity Factor is the proportionality constant between the rock resistivity and the resistivity

of a fluid which fully saturates the rock. Sundberg (1932) first defined this constant, calling it the "resistivity factor" and stated that it was dependent on the porosity, but not on the permeability of a rock. He also calculated this factor for different packings of spherical grains.

The proportionality constant was later termed "formation resistivity factor" by Archie (1942). From laboratory measurements of resistivities of a large number of brine saturated cores from various U.S. Gulf Coast sand formations of diverse porosity and permeability, Archie concluded the following simple relation:

$$R_o = F \cdot R_w. \quad (1)$$

Porosity Resistivity Relation and
Cementation Factor (m)

Archie also experimentally investigated the relation between F and other characteristics of the rock. He observed that F is a function of the rock porosity and that this function can be represented by the formula

$$F = \phi^{-m} \quad (2)$$

which combines with equation 1 to form

$$R_o = R_w \phi^{-m}$$

where ϕ is the porosity of the sand and m is the slope of the line with intercept of zero representing the $F - \phi$ relationship on a log-log graph. For unconsolidated sand packed in the laboratory, Archie found m to be about 1.3 (3).

Resistivity-Water Saturation Relation
and Saturation Exponent (n)

The resistivity of rocks when totally saturated by water is R_o . The resistivity when the rock contains oil and gas is R_t . Martin, et al (1938) and other earlier researchers recognized that oil sands have finite conductivity. This suggests the presence of mineralized water in oil sands due to the percentage of water contained in the pores, and the 1938 paper by Martin, Murray and Gillingham, the first paper on the rock properties, related potential productivity to measured and corrected resistivities.

Archie (1942), by analyzing the results of earlier researchers (Martin, et al), deduced that, for water

saturations down to about 0.15 or 0.20, the following approximate equation applied:

$$S_w = (R_o/R_t)^{\frac{1}{n}} \text{ or } R_t = R_o \cdot S_w^{-n} \quad (3)$$

where S_w is the fraction of the void space filled with water (rock water saturation) and R_t is the resulting resistivity of the sand (formation resistivity). He also showed that the above equations could be written in a different form as follows:

$$S_w = \left(\frac{F \cdot R_w}{R_t} \right)^{\frac{1}{n}} = \left(\frac{\phi^{-m} \cdot R_w}{R_t} \right)^{\frac{1}{n}} = \left(\frac{R_o}{R_t} \right)^{\frac{1}{n}}. \quad (4)$$

So the formation resistivity equation is

$$R_t = \phi^{-m} R_w S_w^{-n}. \quad (5)$$

The above equation describes the resistivity of the rock as a function of porosity, resistivity of formation water, formation water saturation, and the unknown but determinable exponents m and n . The uncertainties inherent in Archie's empirical relations are best realized by his warning, "It should be remembered that the equations given are not precise and represent only approximate relationships". He cautioned against using them in cases more

complex than those upon which the study was based. The greatest weakness of the relations is that they have been derived under laboratory conditions which are very different from underground in situ conditions.

Permeability of Unconsolidated Sands

Permeability is a property of the porous medium and is a measure of the capacity of the medium to transmit the fluids or gas. The measurement of permeability, then, is a measure of the fluid conductivity of the certain material. By analogy with electrical conductors, the permeability represents the reciprocal of the resistance which the porous medium offers to fluid flow.

Darcy's Law (see Figure 1) is as follows:

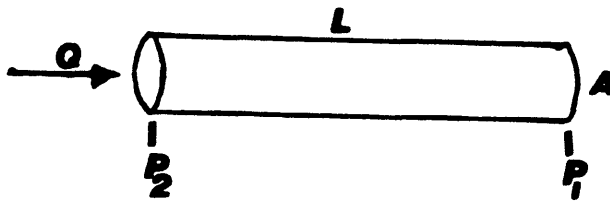


Figure 1. Permeability measurements.

$$Q = (P_2 - P_1) A k / L \cdot \mu \quad (6)$$

where

P-pressure in atmospheres

L-length in cm

μ -viscosity in centipoise

A-cross sectional area in sq. cm

Q-volume rate of flow in ml/sec

k-permeability in darcies.

So the permeability formula for liquid flow is

$$k = \frac{Q \cdot L \cdot \mu}{(P_1 - P_2) A} \quad (7)$$

Capillary Pressure

Capillary pressure is defined as the pressure difference across any fluid surface, due to surface free energy. All surfaces have free energy. If there is no free energy, the surface will mix with the other phase contacted (4).

The concept of surface free energy readily shows on which side the pressure is greatest. Let us take the example of a bubble. Since energy is force applied over a distance, work is required to expand the bubble. Since pressure is the force applied over an area, the pressure is greatest inside the bubble or on the concave

side of the surface. Now capillary pressure is a pressure drop. However, this pressure drop cannot be construed as a pressure gradient, and since capillary pressure is not a pressure gradient, it does not directly provide a potential gradient to cause fluid motion.

Not until one examines capillary pressure drops on the molecular level, does it become evident that they occur over the thickness of a molecular surface, which is essentially zero. So the apparent pressure gradient imposed by capillary pressure can range from infinity to zero depending on the length over which the gradient is measured. A corollary of this is that when determining the direction of flow in multiphase systems, one must look at potential gradients within a single continuous phase to determine the direction of flow.

As the surface free energy is an invariant for a given system, the capillary pressure for a given system is only a function of the radii of curvature. This can be seen in the following fundamental equation of capillarity:

$$P_c = \beta \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \quad (8)$$

where β is surface tension, R_1 and R_2 are the two principal radii of curvature and P_c is the capillary pressure.

Note that capillary pressure has been defined as an equilibrium measure, that is, the interfaces are not moving.

Vertical Capillary Pressure Model

To illustrate this model, let us examine the capillary rise of water in a vertical glass capillary. Inside the capillary, the concave side points up; the pressure above the water interface is higher than below the interface. This would make one think at first glance that the water would be pushed down the capillary rather than pushed up the capillary.

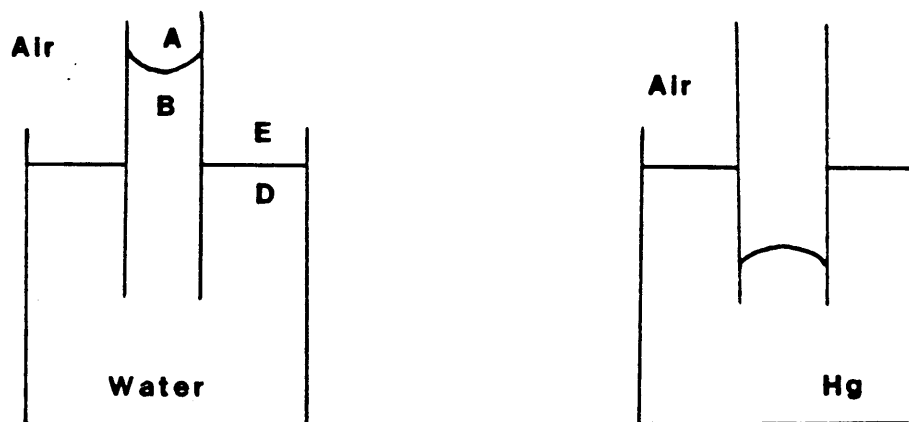


Figure 2. Capillary rise in a vertical capillary

To understand the physics of this, let us picture the capillary (see Figure 2). Points A and B are just

above and below the surface inside the capillary. Since they are essentially at the same height, there is no pressure difference between them due to a hydraulic head. The pressure at point B is less than the pressure at point A due to the capillary pressure discontinuity. Points D and E are similar to points A and B, but they are outside the capillary. The pressure at point E is essentially identical to the pressure at point A. The pressures at points D and E are the same since the surface has essentially an infinite radius of curvature. Thus, the capillary pressure across the interface exterior to the capillary is zero. Since we have the pressure at point D equal to the pressure at point A, the pressure at point D is greater than the pressure at point B. This pressure difference between B and D provides a potential gradient, which causes fluid to move from D to B. Thus, the potential between D and B is essentially equal to the capillary pressure.

The motion of fluid from D to A stops when the potential between these points goes to zero. Thus, a relationship between capillary rise and capillary pressure is attainable.

$$P_c = (\rho_w - \rho_a)g \cdot h \quad (9)$$

where ρ_w and ρ_a are the densities of the water and air, respectively, g is the acceleration due to the gravity and h is the height of capillary rise. Capillary rise is one of the most accurate ways of measuring the capillary pressure. It should be noted that it is an equilibrium measurement (4).

LABORATORY MEASUREMENTS AND CALCULATIONS

In this chapter the variety of work which was carried out will be explained. Included are the method, the quality control and the purpose of measurements along with brief comments on each.

Study of Shape and Size of the Sand Grains

It was determined that a study of sand grain shape was necessary. The purpose was to contribute to the understanding of the work which was going to be carried out later. If any type of sand was more irregular in shape than the others it would affect the later results.

Studying the sand grains under a magnifying device showed that all three types of sands were very regular in shape. They were all very well sorted and spherical, or very close to spherical, in shape. In comparison, the most regular shape grains were found in the 20/40 medium sand. The more irregular shape grains were found in the 100 mesh fine sand. Coarse sand the 12/20 was in between these two.

Measurement of Porosity and
Calculation of Matrix Density

A certain volume of sand was weighed dry in air to get W_d . This sample was then saturated with water ($\rho_w = 1.0\text{gr/ml}$) and weighed again to get W_w . By using the formula below, porosity (ϕ) was calculated (5).

$$\phi = \text{Pore volume/Total volume} \quad (10)$$

The results are listed below.

For coarse sand:

total volume = 5.6ml,

pore volume = 2.2ml,

$\phi = 2.2/5.6 = .39 \quad \phi = 39\%$.

For medium sand:

total volume = 4.9ml,

pore volume = 1.9ml,

$\phi = 1.9/4.9 = .38 \quad \phi = 38\%$.

For fine sand:

total volume = 5.4ml,

pore volume = 1.95ml,

$\phi = 1.95/5.4 = .36 \quad \phi = 36\%$.

Calculation of Matrix Densities

A calculation of the matrix densities of the samples by using known and measured parameters was performed.

In the previous step the porosities of sand samples were found. Since dry weight and total volume of the sample sands were known, by subtracting the pore volume from the total volume the matrix volume was determined. Then using the equation below

$$\rho_m = W_d / (V_t (1 - \phi)) \quad (11)$$

the matrix density (ρ_m) was found and the results are listed below.

For coarse sand:

matrix volume = 3.4ml,

matrix weight = 9gr,

$\rho_m = 9/3.4 = 2.647\text{gr/ml}$.

For medium sand:

matrix volume = 3.0ml,

matrix weight = 7.98gr,

$\rho_m = 7.98/3.0 = 2.66\text{gr/ml}$.

For fine sand:

matrix volume = 3.45 ml,

matrix weight = 9.15gr,

$\rho_m = 9.15/3.45 = 2.65\text{gr/ml}$.

The calculated matrix densities were considered satisfactory because they were quite close to the density of quartz (2.65 gr/ml).

Measurement of Permeability

The permeability of each type of sand was measured by a vertical flow method (6).

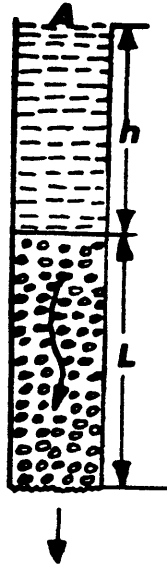


Figure 3. Measurement of permeability; vertical flow downward with pressure head.

Parameters for the apparatus used were as follows:

$$h = 10\text{cm}$$

$$L = 9.5\text{cm} \quad r = 1.9\text{cm}$$

$$g = 980\text{cm/sec}$$

$$\mu = 1.0 \text{ centipoise}$$

$$Q = \frac{k \cdot A}{\mu} \cdot \rho_w g \left(\frac{h}{L} + 1\right) 10^{-3} \quad (12)$$

$$k = \frac{Q \cdot \mu}{A \cdot \rho_w \cdot g \left(\frac{h}{L} + 1\right) 10^{-3}} = \text{darcy}$$

Time was measured for the same amount of water to go through each of the samples.

For coarse sand, time measured 2.0 sec.

For medium sand, time measured 4.4 sec.

For fine sand, time measured 164.0 sec.

Calculated permeabilities from equation (12) are listed.

For coarse sand, $k = 251.8$ mdarcy.

For medium sand, $k = 114.6$ mdarcy.

For fine sand, $k = 3.07$ mdarcy.

Permeabilities were also measured by using the Ruska liquid permeameter in the Petroleum Engineering Department and are listed.

For coarse sand, $k = 280$ mdarcy.

For medium sand, $k = 118$ mdarcy.

For fine sand, $k = 3.5$ mdarcy.

The permeabilities which were found by the two different methods were surprisingly similar.

Measurement of Resistivity R_o and R_t

The experimental set up is shown in Figure 4.

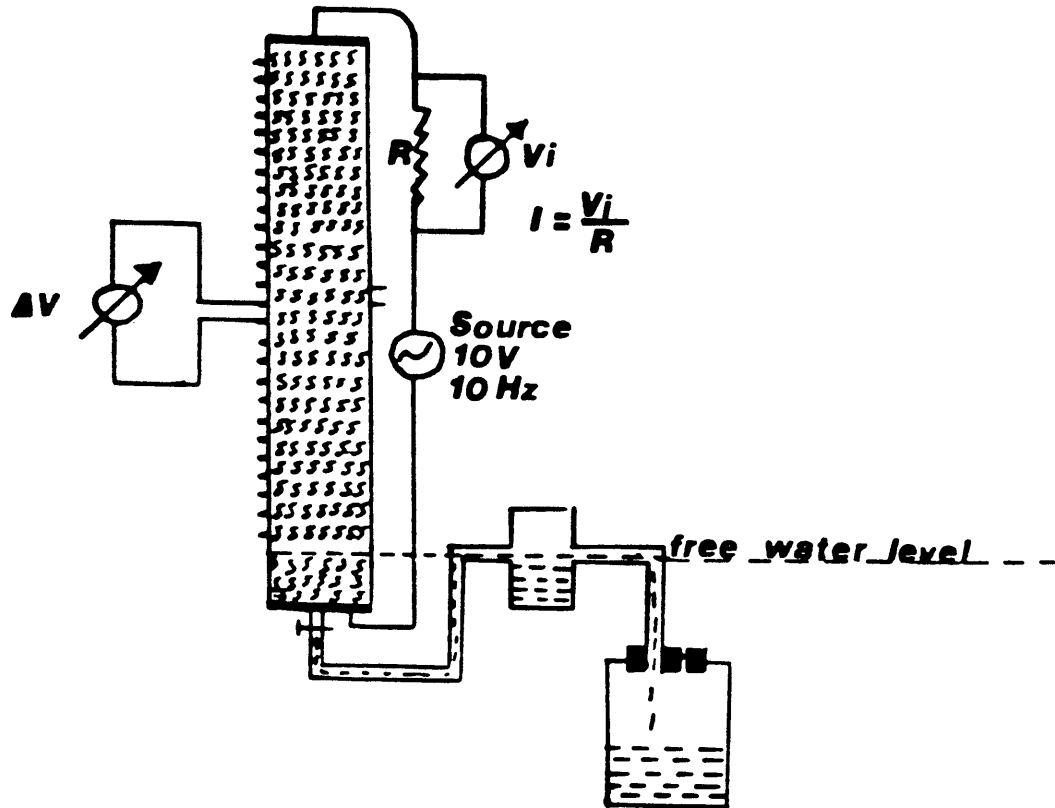


Figure 4. Method of resistivity (R_t and R_o) measurements.

A plastic pipe 140cm long and 9.31cm in diameter was used. One hundred twelve electrodes for measuring the potential differences were placed 1cm apart starting 15cm above the bottom of the pipe. One of the current electrodes was at the bottom of the pipe while the other one was at

the top. A Hewlett Packard 3676A digital multimeter was used for the measurements. The source was a Tektronix FG501A function generator. Source frequency was 10Hz and the voltage applied to the sample was 10V.

A little reservoir which was attached 15 cm above the bottom of the pipe enabled the author to keep the free water level constant at the bottom of the pipe. This little reservoir was connected to a bigger one where all water coming out of the pipe was stored. Precautions were taken to prevent the loss of water by evaporation.

Before it was filled with sand the pipe was filled with brine and the resistivity of the brine was measured ($R_w = 0.14\text{ohm-m}$) at room temperature.

Later, a known amount of brine was kept in the column and then sand was poured into the pipe and carefully packed. More brine and more sand were added until a column of sand which was 100% brine saturated was obtained. The total amount of water added to the column was recorded.

Current passing through the sample in the column was calculated by measuring the voltage drop over a known resistor R_1 . Potential differences between electrodes spaced every one centimeter were measured. Since the geometrical factor of the sample was known, resistivities

could be calculated. The experiment was first carried out with a 100% saturated column to determine the R_o values. Later a valve at the bottom of the pipe was opened, and the column was left to reach its capillary equilibrium. For each sample, column measurements were taken one day, two days, three days and one week later to observe the changes on R_t values along the column.

Measurement of Water Resistivity, R_w

A small apparatus was made to determine the resistivity of brine which was used in the experiment.

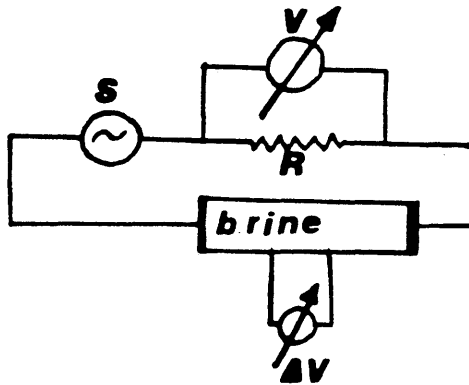


Figure 5. Measurement of R_w .

By using equation (13) R_w was found to be 0.14 ohm-m.

$$I = V/R$$

$$R_w = G \cdot \Delta V / I \quad (13)$$

It was confirmed that the resistivity of water used in the experiment remained constant. This was done by minimizing the loss of water by evaporation and by measuring R_w several times again during the experiment.

Calibration and Test of Equipment Used
in Resistivity Measurements

The author wanted to make sure before taking any measurements that the source and voltmeter were quite proper for the experiment and that they gave accurate and consistent results. The following test was carried out to check this.

Known resistors were measured by ohm-meter, and these were considered known values (see Figure 6).

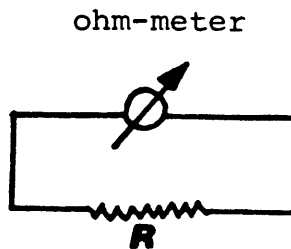


Figure 6. Simple measurement of resistance.

The resistance of the same resistors was measured by the method shown below (see Figure 7). It was important to

get the same results by this method because this was the basis of the method used in the final resistivity measurements.

Current passing through resistor R was calculated by measuring the voltage drop V_i over known resistor R_i

$$I = V_i / R_i.$$

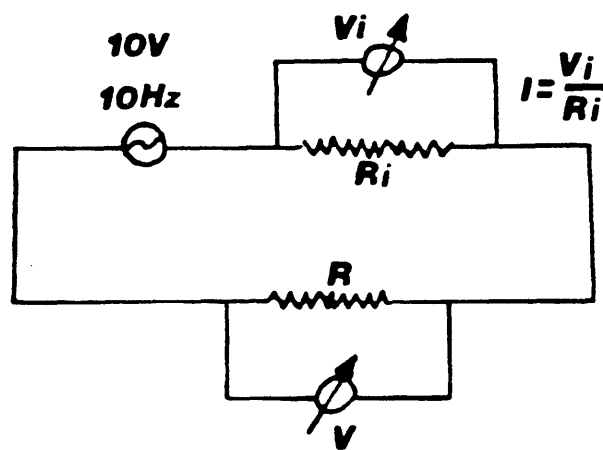


Figure 7. Measurement of resistance by simulation of resistivity measurement.

The voltage drop over the resistor (R) was measured. The resistance of the resistor R was calculated by $R = \frac{V}{I}$. This was repeated for 7 different resistors. These were called measured values. As is shown in Figure 8, a plot of known values vs measured values is a line. Table 1 also shows quantitatively how close the results were.

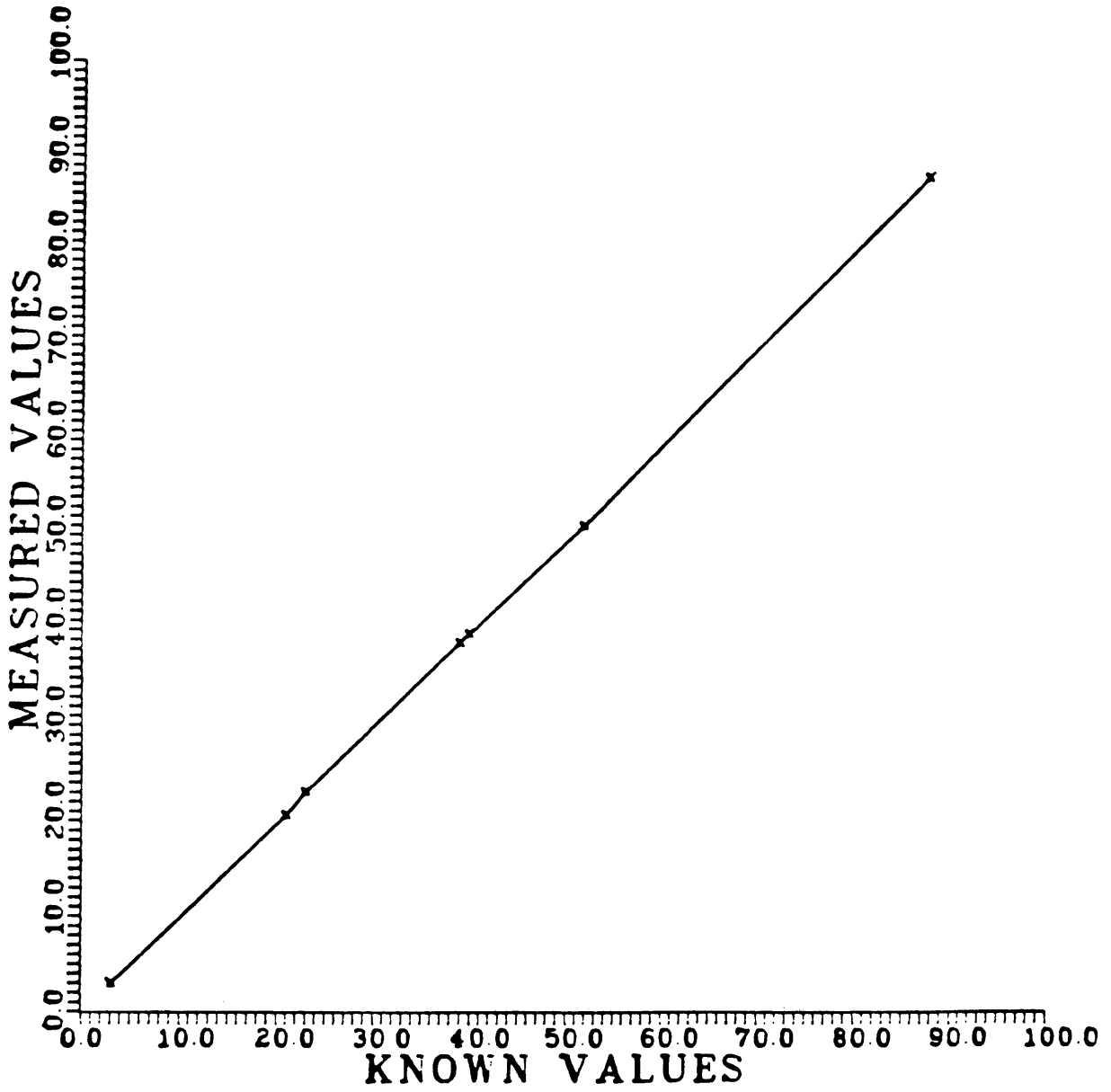


Figure 8. Quality control of the resistivity measurements.

Table 1. Quantitative comparison of known and measured resistance values.

<u>Known Values</u> (ohm)	<u>Measured Values</u> (ohm)
3.0	3.04
21.0	20.64
23.0	23.06
39.0	38.82
40.0	39.73
52.0	51.14
88.0	87.87

It was decided that the equipment was proper and consistent.

Calculation of Formation Factor (F) and
Cementation Factor (m)

In Archie's equation all necessary parameters were calculated for all three types of sand to calculate formation factor and cementation factor.

R_w remained constant at 0.14 ohm-m for the entire experiment. Using equation (1), $F = R_o / R_w$, formation factor F was calculated from measured values of R_o and the results are listed below.

For coarse sand:

$$R_o = 0.52 \text{ ohm-m,}$$

$$F = 0.52/0.14 = 3.71.$$

For medium sand:

$$R_o = 0.54 \text{ ohm-m,}$$

$$F = 0.54/0.14 = 3.857.$$

For fine sand:

$$R_o = 0.58 \text{ ohm-m,}$$

$$F = 0.58/0.14 = 4.14.$$

Cementation factors could now be determined using $F = \phi^{-m}$ and are listed.

For coarse sand:

$$\phi = .39, \quad F = 3.71,$$

$$m = -\log 3.71 / \log 0.39 = 1.392.$$

For medium sand:

$$\phi = .38, \quad F = 3.857,$$

$$m = -\log 3.857 / \log 0.38 = 1.395.$$

For fine sand:

$$\phi = .36, \quad F = 4.14,$$

$$m = -\log 4.14 / \log 0.36 = 1.391.$$

Cementation factors for all three types were very close values, m was a little higher for medium sand than the others. A possible explanation is that the medium sand had the most regularity in grain shape so it was quite possible that it had better packing. Archie found m to be about 1.3 for unconsolidated natural sand deposits. Knowing that it would be quite difficult to find such clean and well sorted sands in nature as those used in this experiment, these results for cementation factors have been considered very reasonable by the author.

Calculation of Saturation Exponent (n)

At this stage R_o values along the sand column and R_t values along the sand column one day, two days, three days and one week later were known.

Every time a resistivity measurement was taken, the amount of water which had come out of the column was recorded.

Since it was known how much water was used in the 100% saturated column, by measuring the amount of water which came out of the column, the amount of water which was left in the column was determined.

$$\left\{ \begin{array}{l} \text{Volume of water} \\ \text{still in the} \\ \text{column} \end{array} \right\} = \left\{ \begin{array}{l} \text{Volume of water} \\ \text{used to start} \\ \text{the experiment} \end{array} \right\} - \left\{ \begin{array}{l} \text{Volume of water} \\ \text{out of the} \\ \text{column} \end{array} \right\}$$

To determine the correct saturation exponent before starting the saturation calculation, the following equation was used

$$R_t = \phi^{-m} R_w S_w^{-n} .$$

In the above formula, other than S_w and n , all parameters were calculated or measured. Since the volume of water which was still in the column was known, the calculation of the correct n value was possible.

Starting from $n = 1.3$, the water saturation for every cm of the column was determined. Since the porosity of the sand in the column and the total volume of the one cm long pipe was known, the amount of water in every cm of the column was **calculated**. These values were later

integrated to find the total amount of water in the column. The calculations were repeated for increasing n values using an n value increment of 0.1.

A graph was drawn for every type of sand for these results. Tables 2, 3 and 4 were prepared for better quantitative comparison. After studying the tables and graphs it was decided to take $n = 2.0$ for every type of sand (see Figures 9, 10, 11).

Calculation of Water Saturation (S_w)

In the equation, $R_t = \phi^{-m} R_w S_w^{-n}$, everything was calculated step by step up to this stage except S_w . So water saturation was found using

$$S_w = (R_o/R_t)^{\frac{1}{n}}; \text{ for } n = 2.0$$

Water saturation values were calculated for every cm of the column this way. A graph of height (cm) vs water saturation (%) was drawn for every resistivity measurement taken.

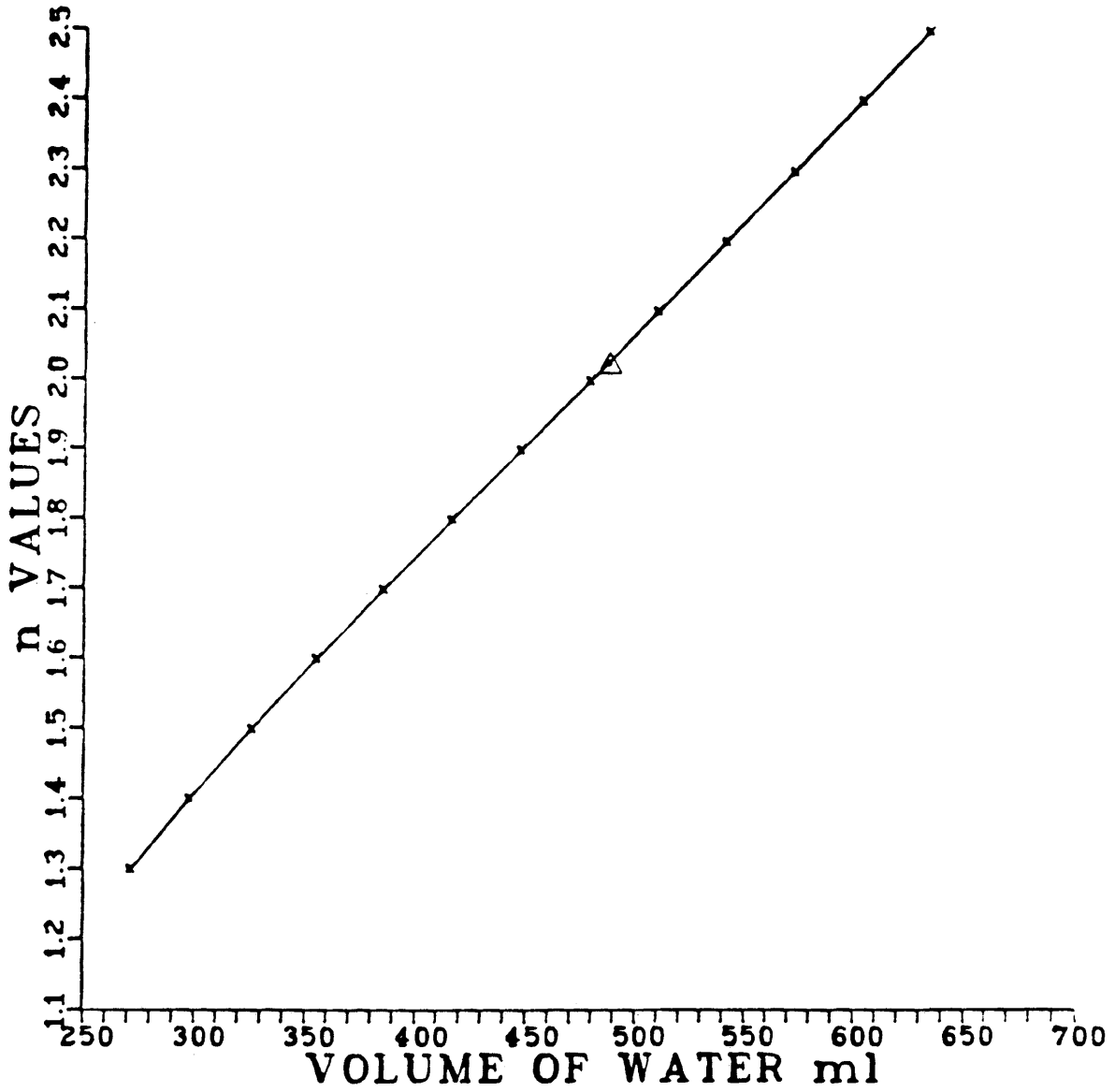


Figure 9. Coarse sand, correlation of n values, total volume of water in the column = 485 ml.

Table 2. Quantitative comparison of the calculated total amount of water for varying n values. Total amount of water in the coarse sand column is 485 ml.

<u>n values</u>	<u>Calculated total amount of water in the column (in ml)</u>
1.3	271.2792
1.4	297.7084
1.5	325.7799
1.6	355.1312
1.7	385.4373
1.8	416.4142
1.9	447.8179
2.0	479.4419 (485)
2.1	511.1130
2.2	542.6880
2.3	574.0491
2.4	605.1011
2.5	635.7672

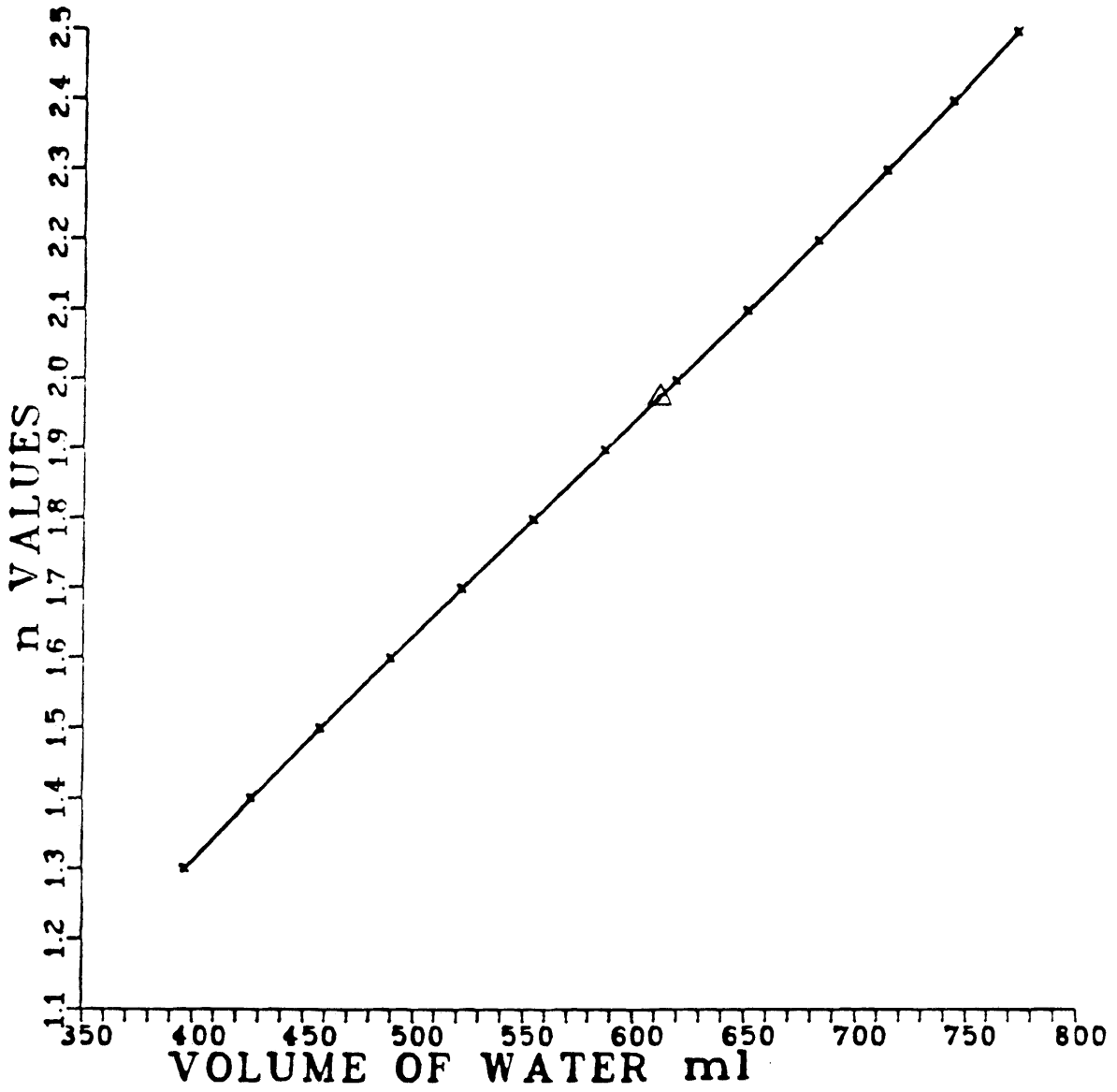


Figure 10. Medium sand, correlation of n values, total volume of water in the column = 615 ml.

Table 3. Quantitative comparison of the calculated total amount of water for varying n values. Total amount of water in the medium sand column is 615 ml.

<u>n values</u>	<u>Calculated total amount of water in the column (in ml)</u>
1.3	396.6189
1.4	426.6851
1.5	457.8616
1.6	489.8055
1.7	522.2214
1.8	554.8603
1.9	587.5162
2.0	620.0205 (615)
2.1	652.2376
2.2	684.0597
2.3	715.4024
2.4	746.2009
2.5	776.4066

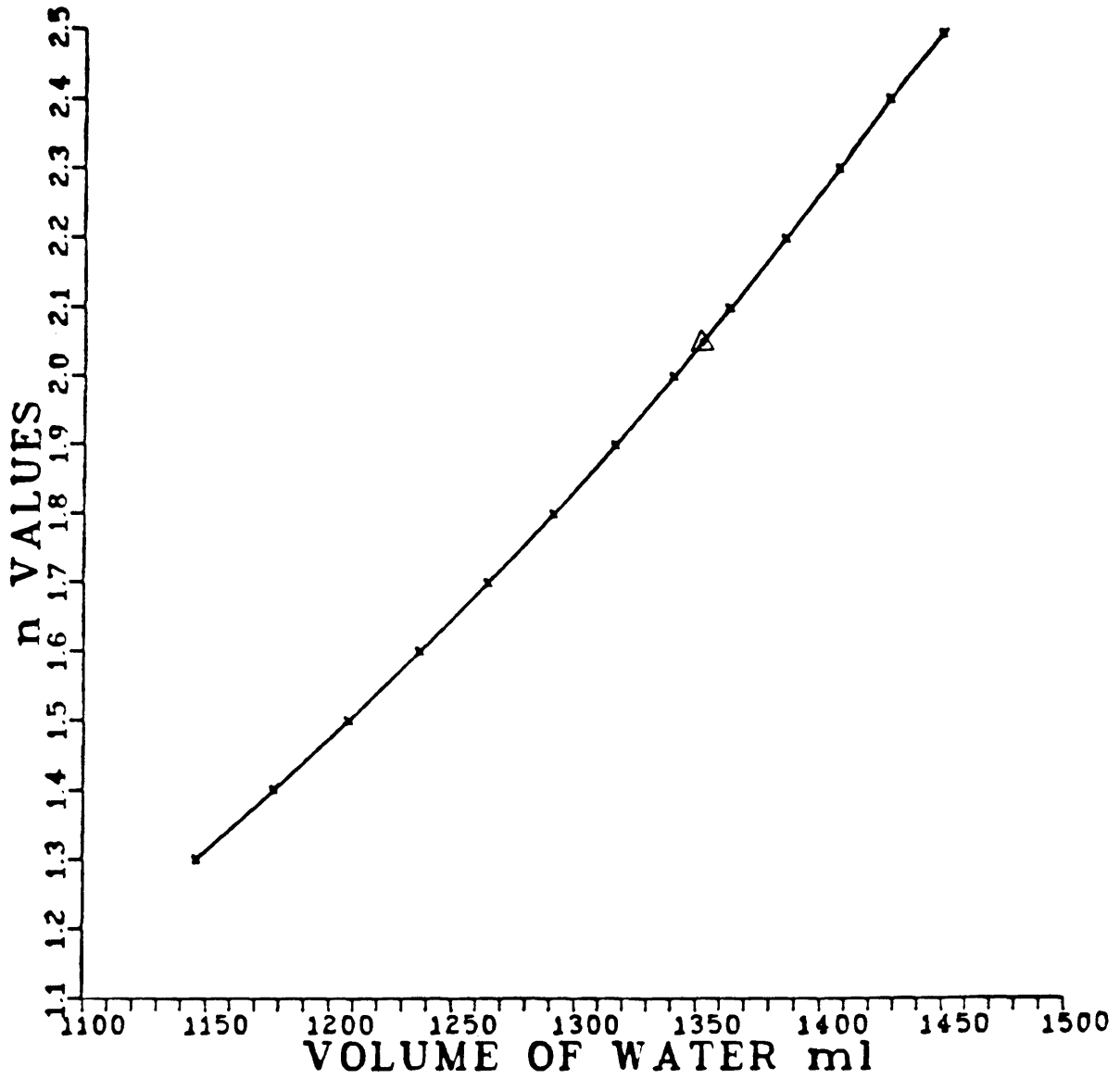


Figure 11. Fine sand, correlation of n values, total volume of water in the column = 1351 ml.

Table 4. Quantitative comparison of the calculated total amount of water for varying n values. Total amount of water in the medium sand column is 1351 ml.

<u>n values</u>	<u>Calculated total amount of water in the column (in ml)</u>
1.3	1146.034
1.4	1177.857
1.5	1208.289
1.6	1237.401
1.7	1265.258
1.8	1291.919
1.9	1317.440
2.0	1341.876 (1351)
2.1	1365.280
2.2	1387.702
2.3	1409.191
2.4	1429.795
2.5	1449.559

PRESENTATION OF THE RESULTS
OF RESISTIVITY MEASUREMENTS

As a result of the resistivity measurements, R_o and R_t versus height (cm) curves were determined. After it was determined that n for each pack is approximately 2.0, water saturation (%) versus height (cm) curves were determined. These S_w vs. height curves can also be interpreted as water saturation (%) versus capillary pressure but it would be necessary to multiply the vertical axis by the density of the brine used and by the acceleration of gravity. Multiply the vertical axis by

$$\rho_f \approx 1.01 \text{ gr/ml}$$

$$g \cdot \rho_f = 980 (1101) = 9.89.8$$

This comes from the definition of capillary pressure.

$$P_c = \rho_f \cdot g \cdot h$$

The results of the resistivity measurements can now be presented. Coarse sand, medium sand, fine sand and layered sand will be presented, respectively.

On every plot a straight line parallel to the X axis from the 15th. cm of the vertical axis shows the height of the water table.

$$\frac{9.89}{1} \cdot \frac{\text{cm}}{1.01} = \text{cm}$$

Coarse Sand Column

The column was prepared with the 12/20 coarse sand first. After having the column 100% brine saturated R_o resistivity measurements were made. Later the valve at the bottom of the column was opened and sand was allowed to reach its capillary equilibrium. It was observed that equilibrium was reached very rapidly. Most of the water in the column came out within the first two hours. The first resistivity measurements for R_t values were made 24 hours after the valve was opened. As is shown in Figure 12, R_o was almost a vertical line as was expected. The behaviour of R_t curves and the S_w curves follows the formula, $S_w = (R_t/R_o)^{\frac{1}{n}}$.

Figures 12 through 20 are R_o and R_t versus height and S_w versus height curves for coarse sand and were determined one day, two days, three days and one week after the valve was opened and the sand column was tending toward equilibrium. As is shown in Figure 20 the S_w curve has shown very little change one day and one week later.

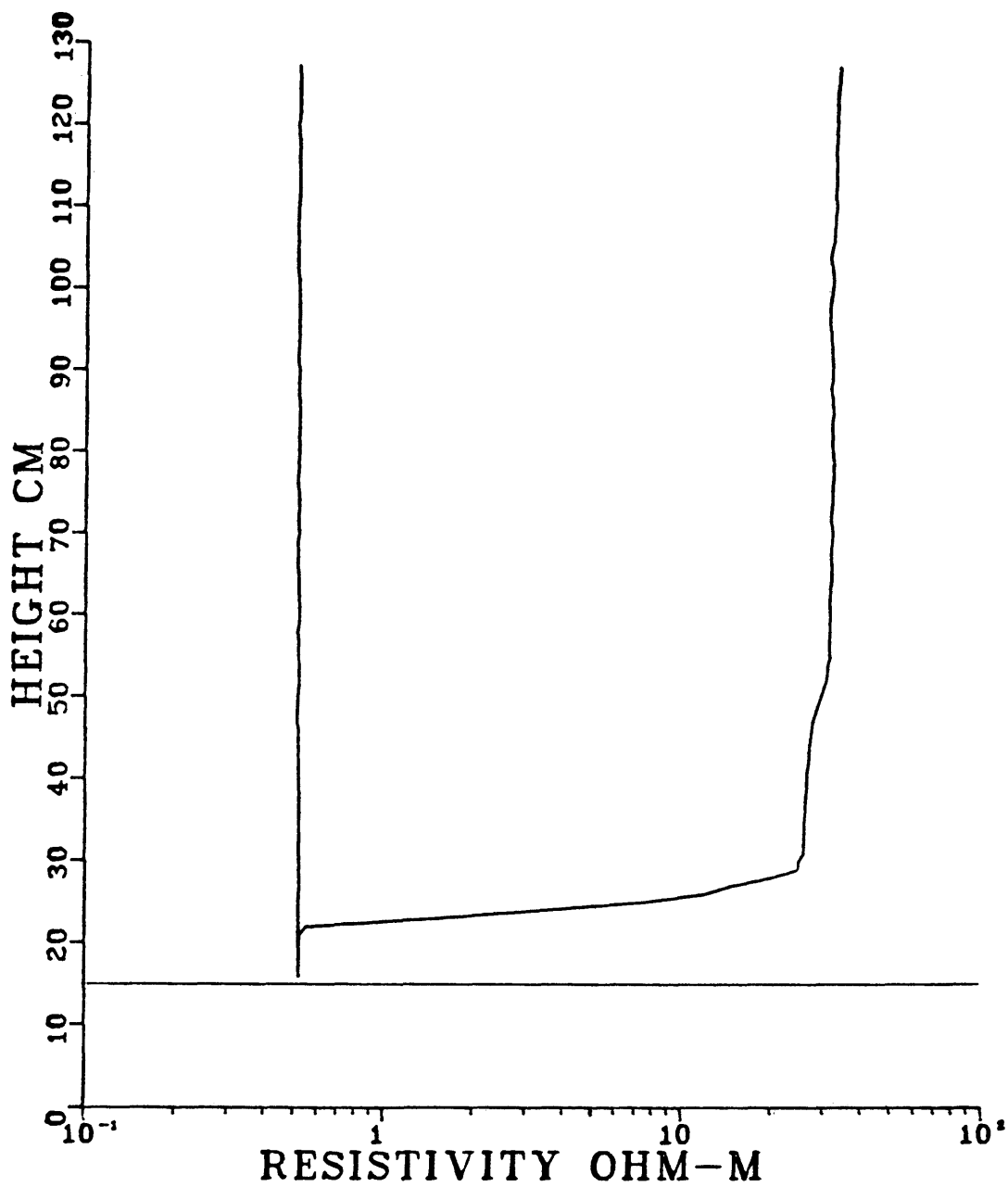


Figure 12. Coarse sand column R₀ and one day later R_t values.

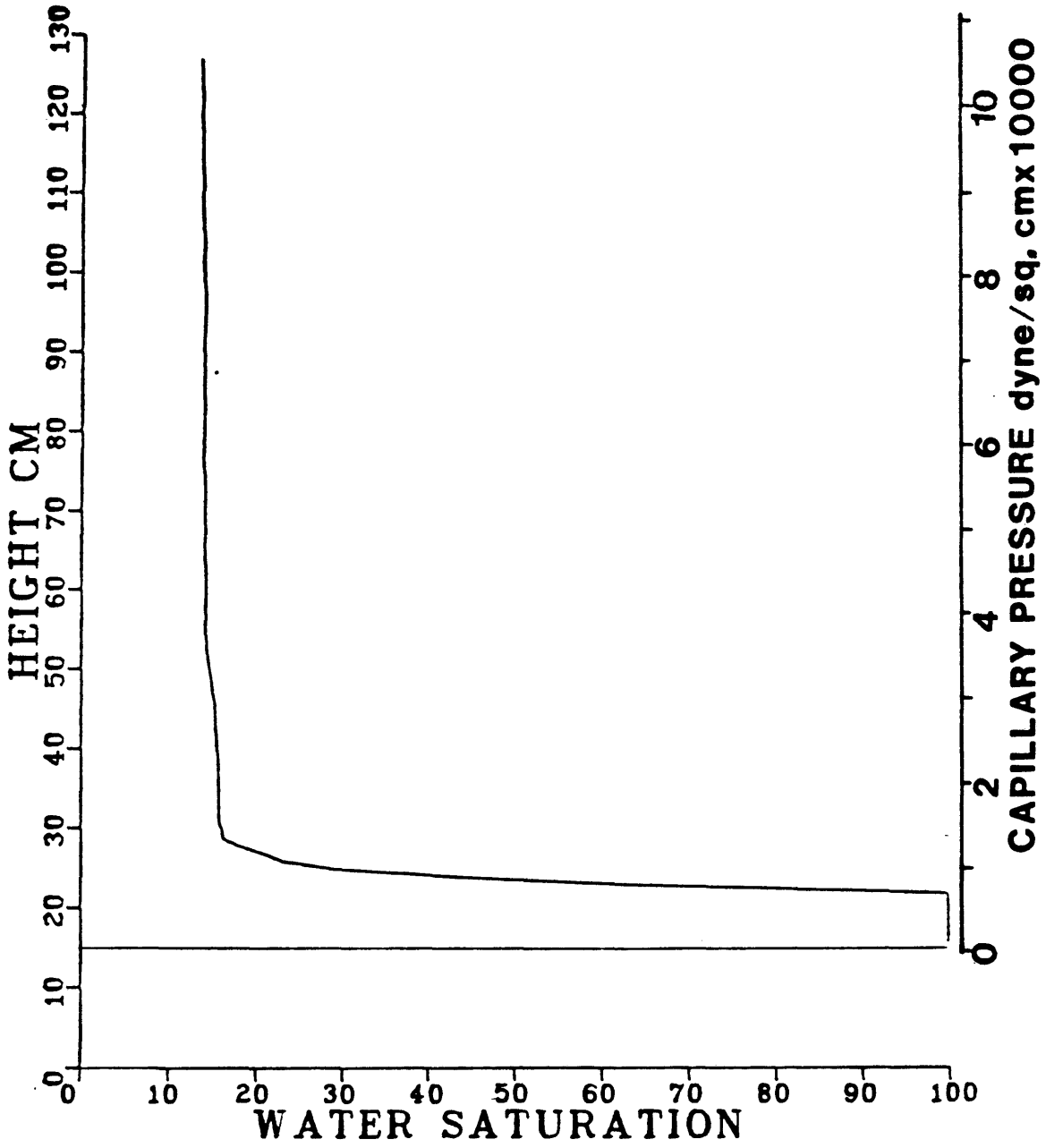


Figure 13. Coarse sand column $n = 2.0$, one day later
 S_w vs. P_c .

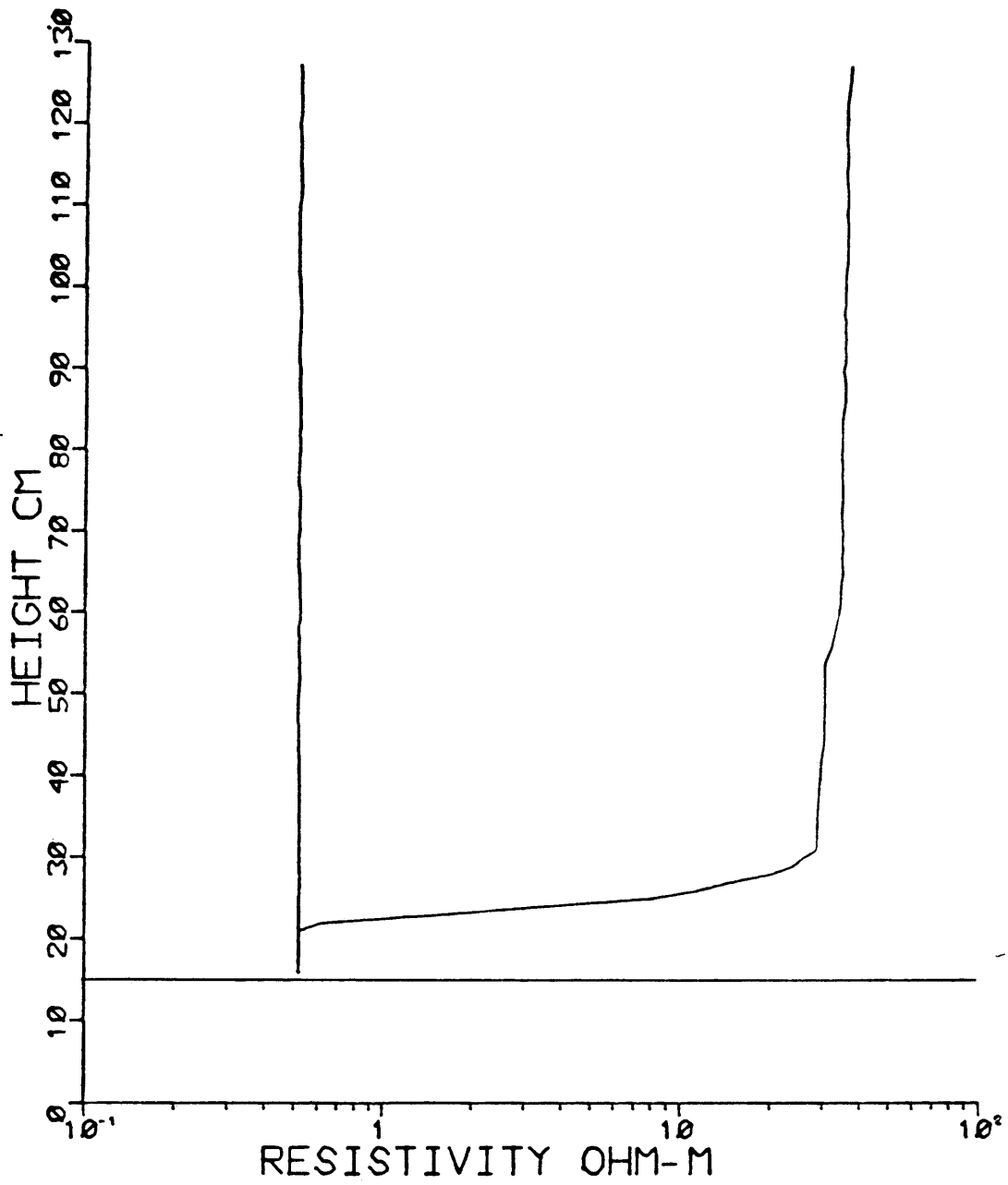


Figure 14. Coarse sand column R_o and two days later R_t values.

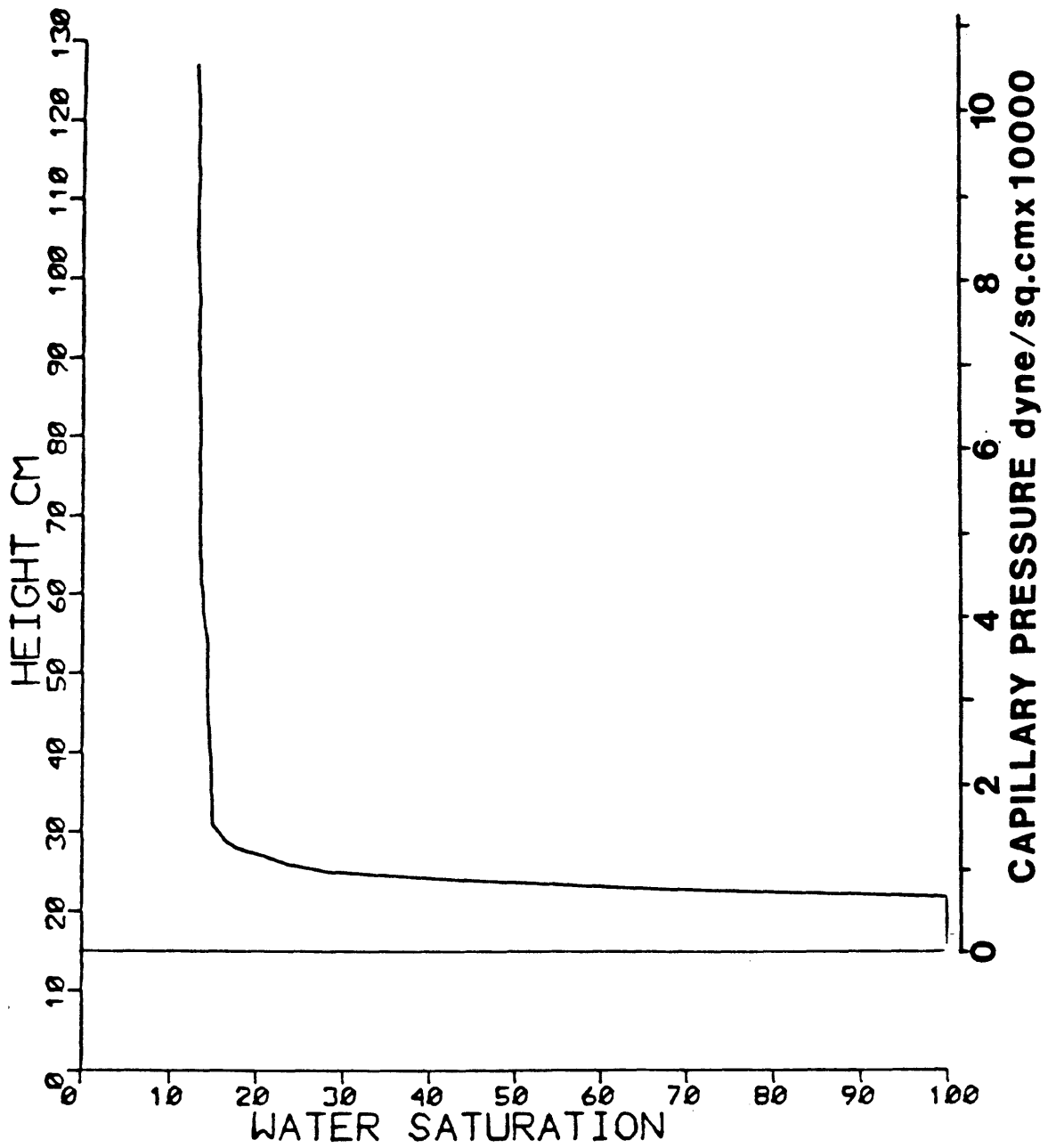


Figure 15. Coarse sand column $n = 2.0$, two days later
 S_w vs. P_c .

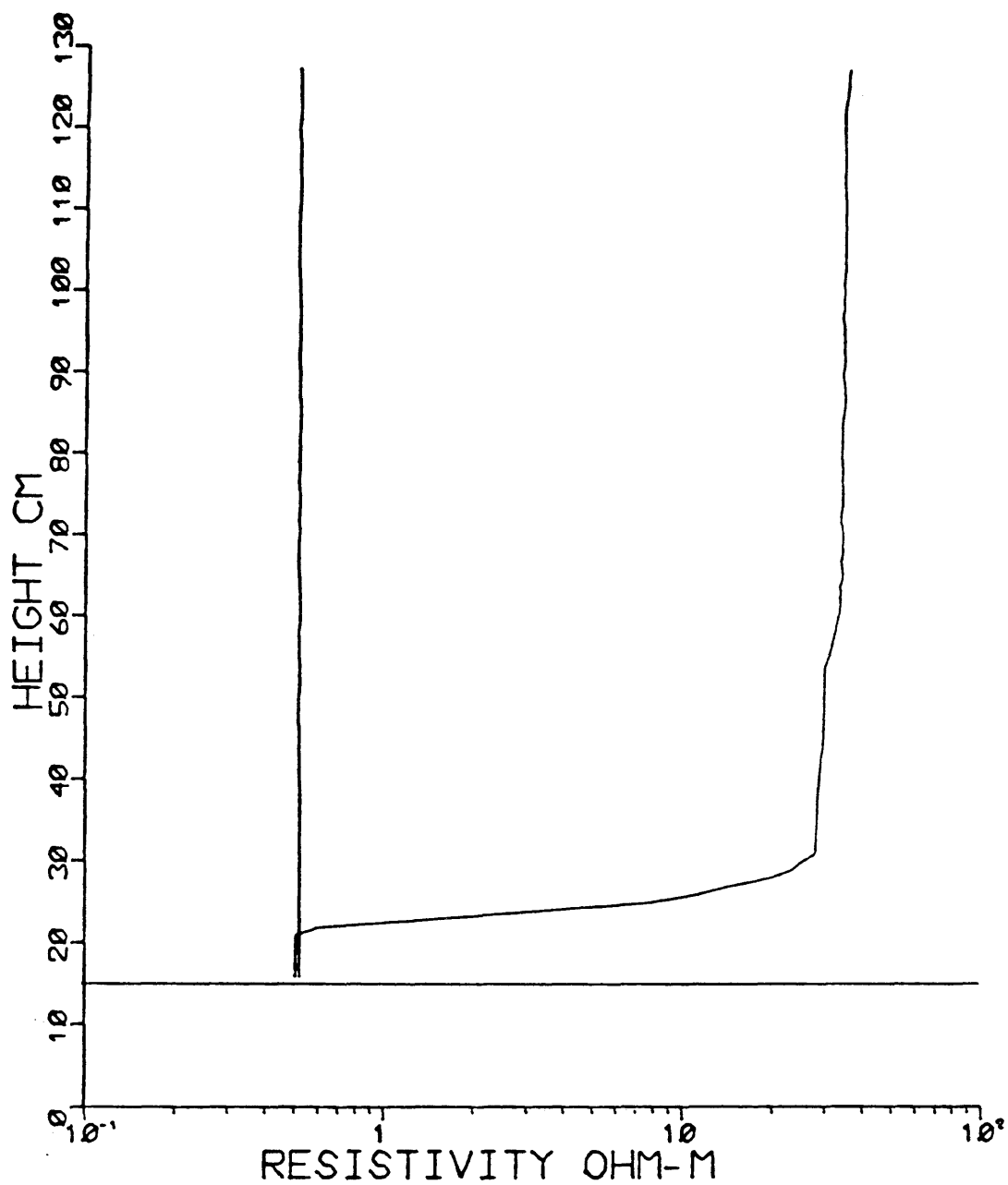


Figure 16. Coarse sand column R_o and three days later R_t values.

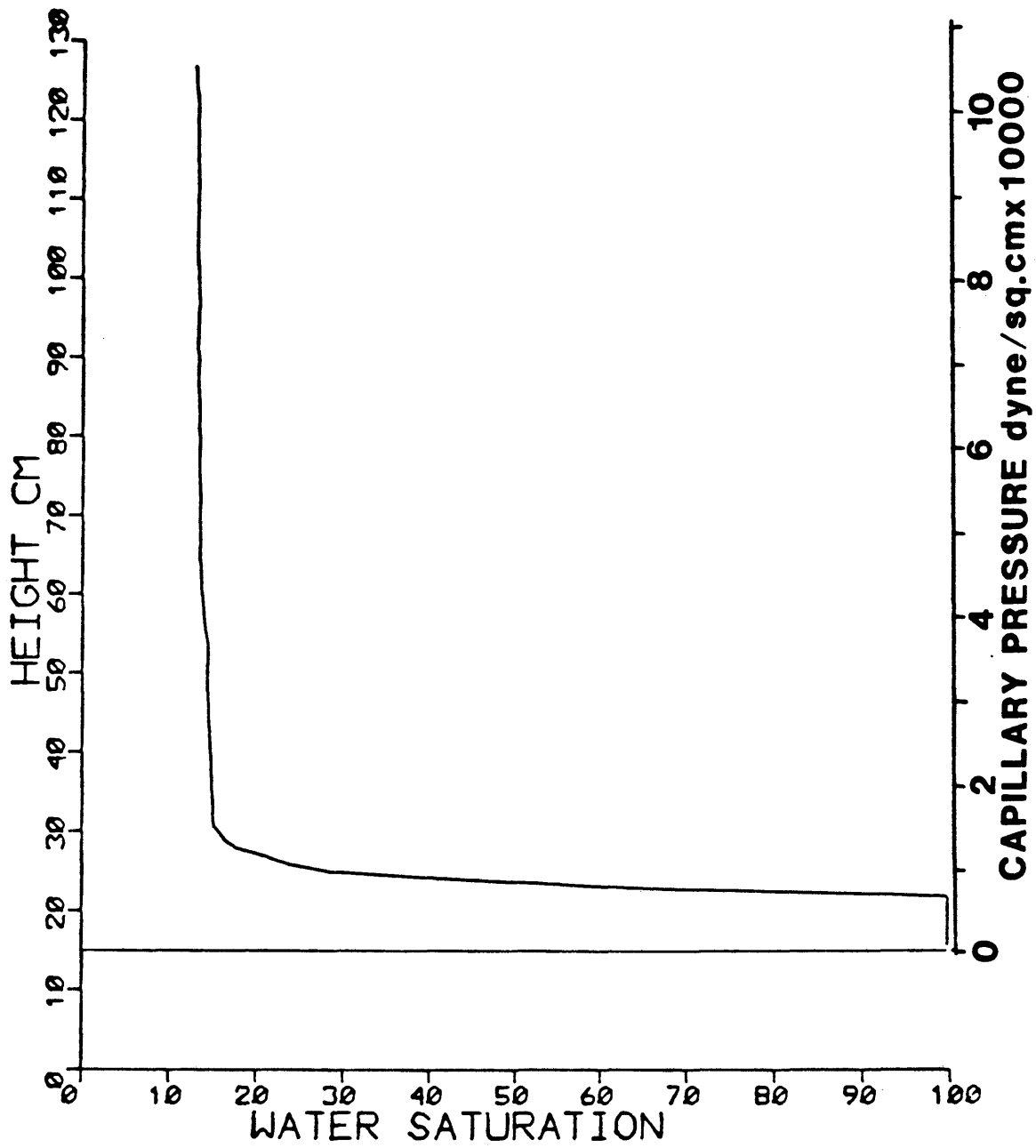


Figure 17. Coarse sand column $n = 2.0$, three days later
 S_w vs. P_c .

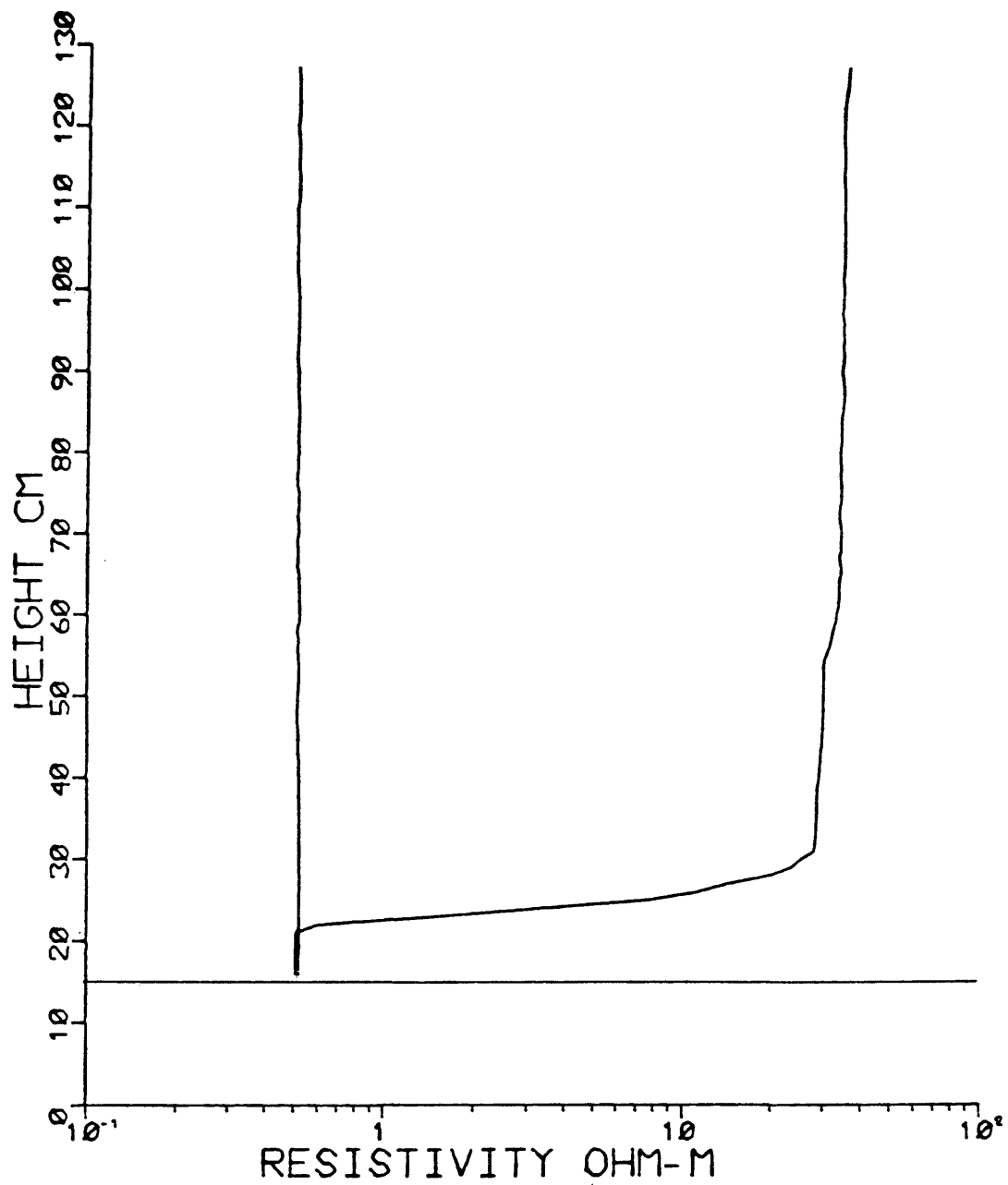


Figure 18. Coarse sand column R_o and one week later R_t values.

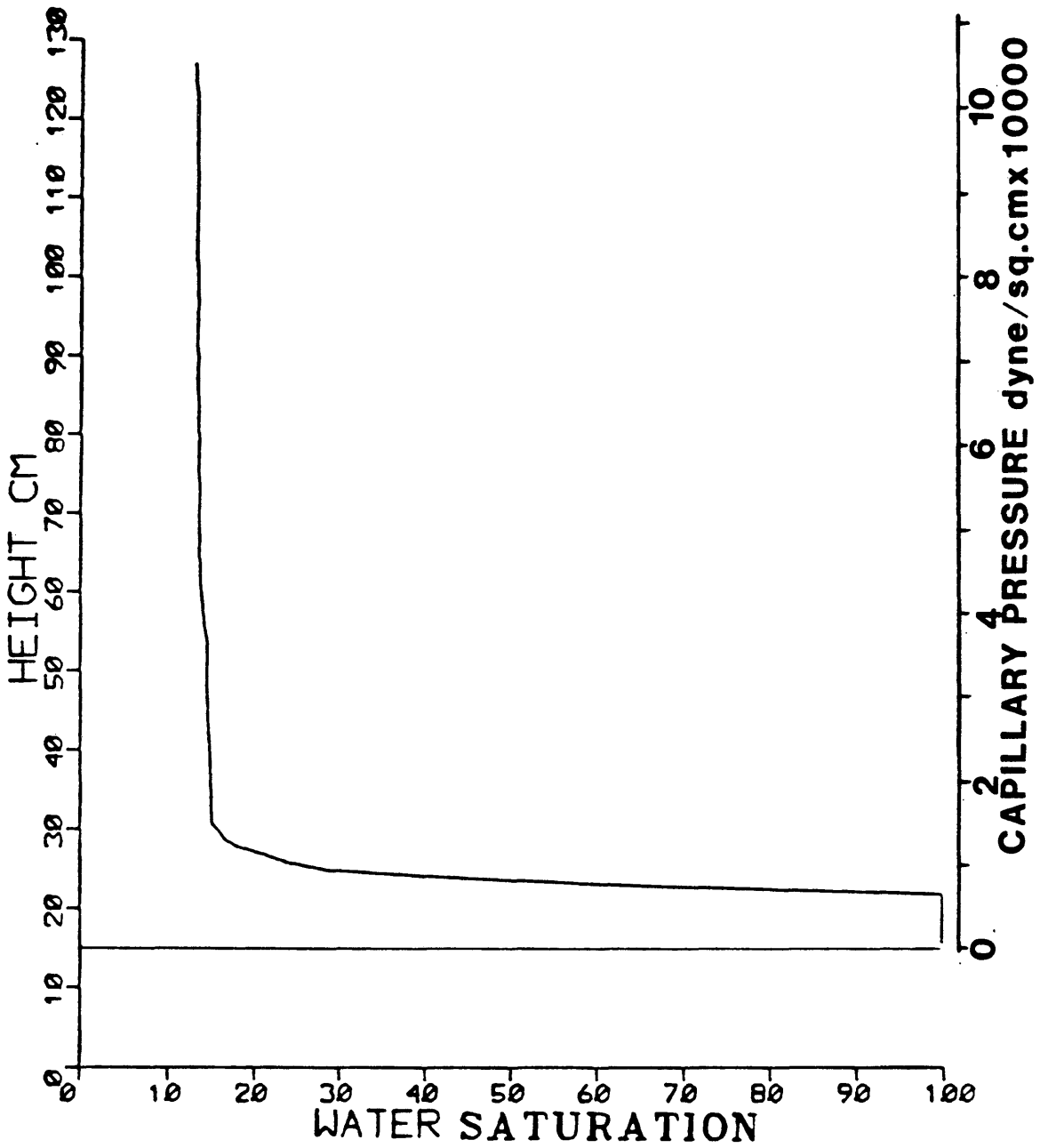


Figure 19. Coarse sand column $n = 2.0$, one week later S_w vs. P_c .

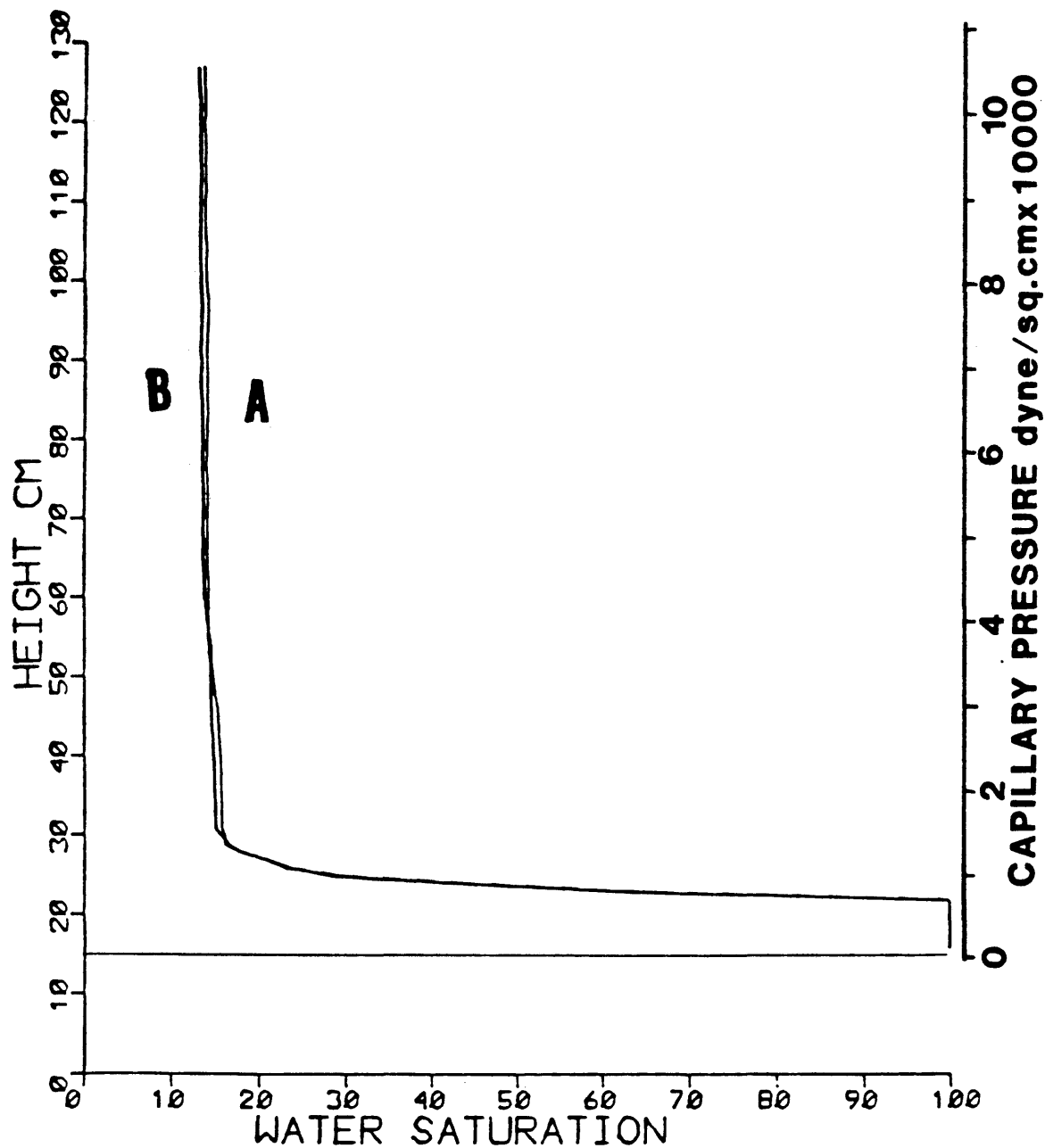


Figure 20. Coarse sand column - correlation of $S_w - P_c$ curves; A-one day later, B-one week later.

Medium Sand Column

The column was filled with the 20/40 medium sand this time. Resistivity measurements were carried out for R_o values first. Later the valve at the bottom of the column was opened. It was observed that the medium sand column took three times as long to reach its capillary equilibrium as the coarse sand column. Resistivities found for the 100% water saturated column were again constant (see Figure 21). As is shown in Figures 21 through 28, R_o and R_t versus height and S_w versus height values were determined for one day, two days, three days and one week later.

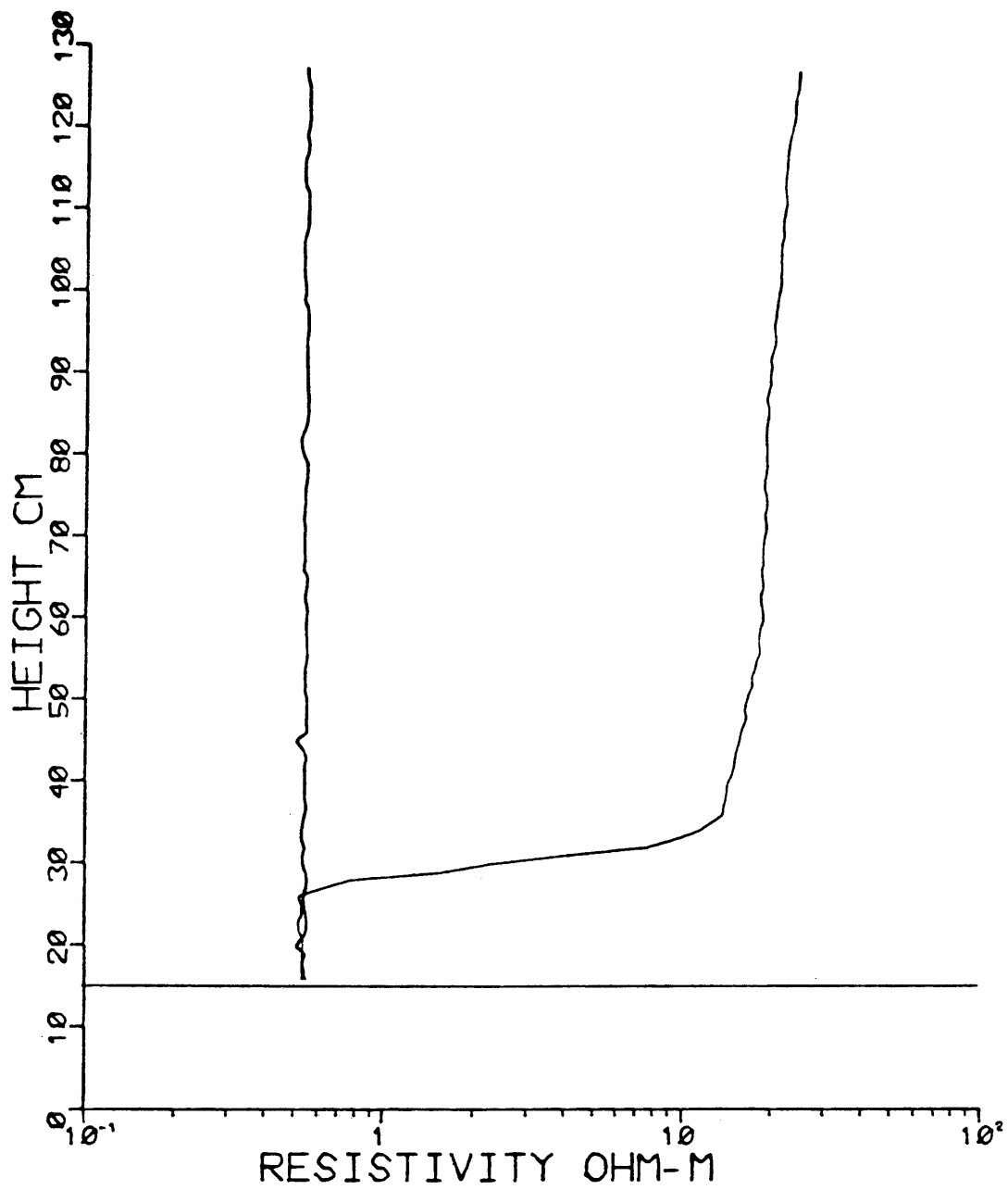


Figure 21. Medium sand column R_0 and one day later R_t values.

1
2

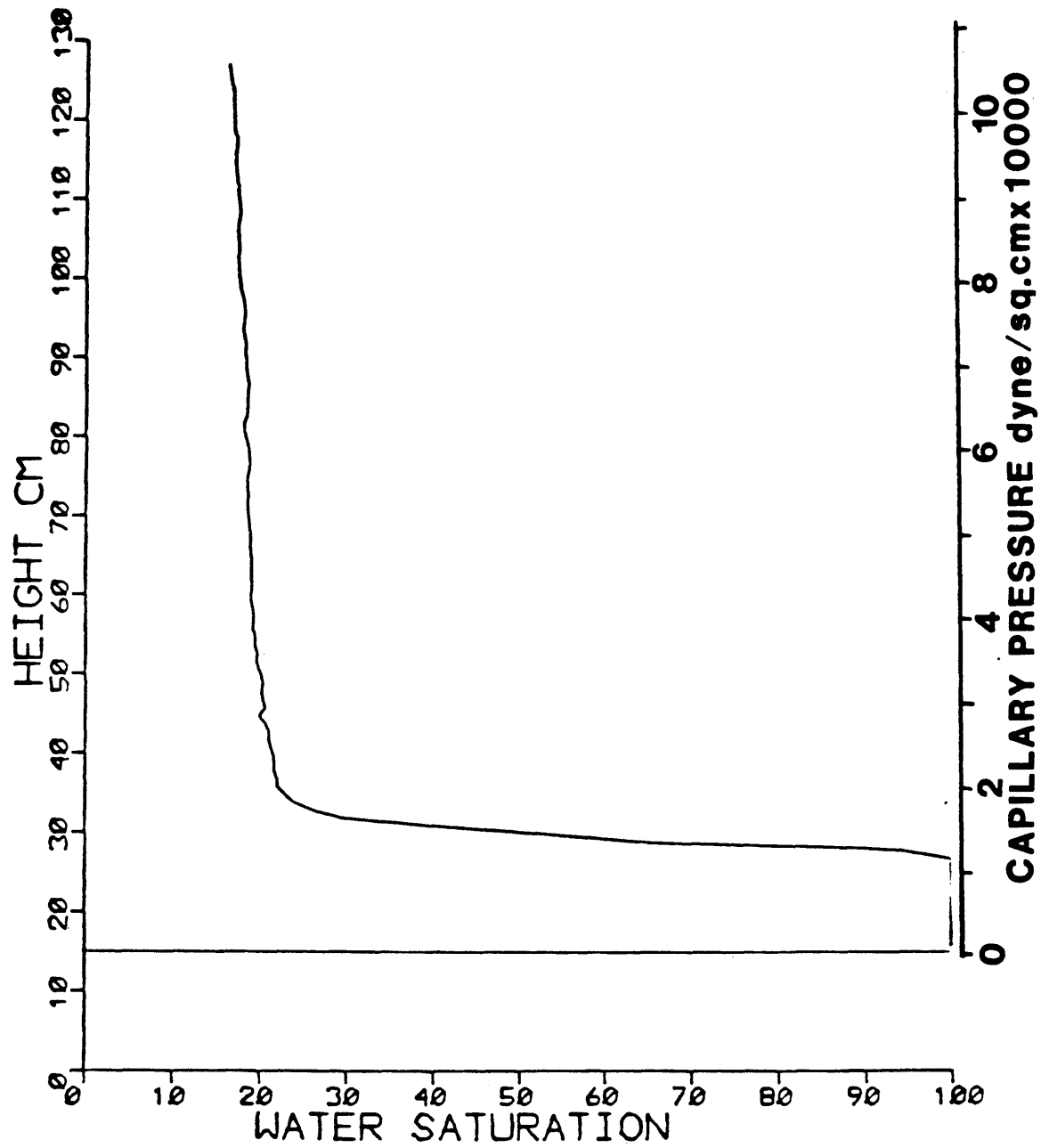


Figure 22. Medium sand column $n = 2.0$, one day later
 S_w vs. P_c .

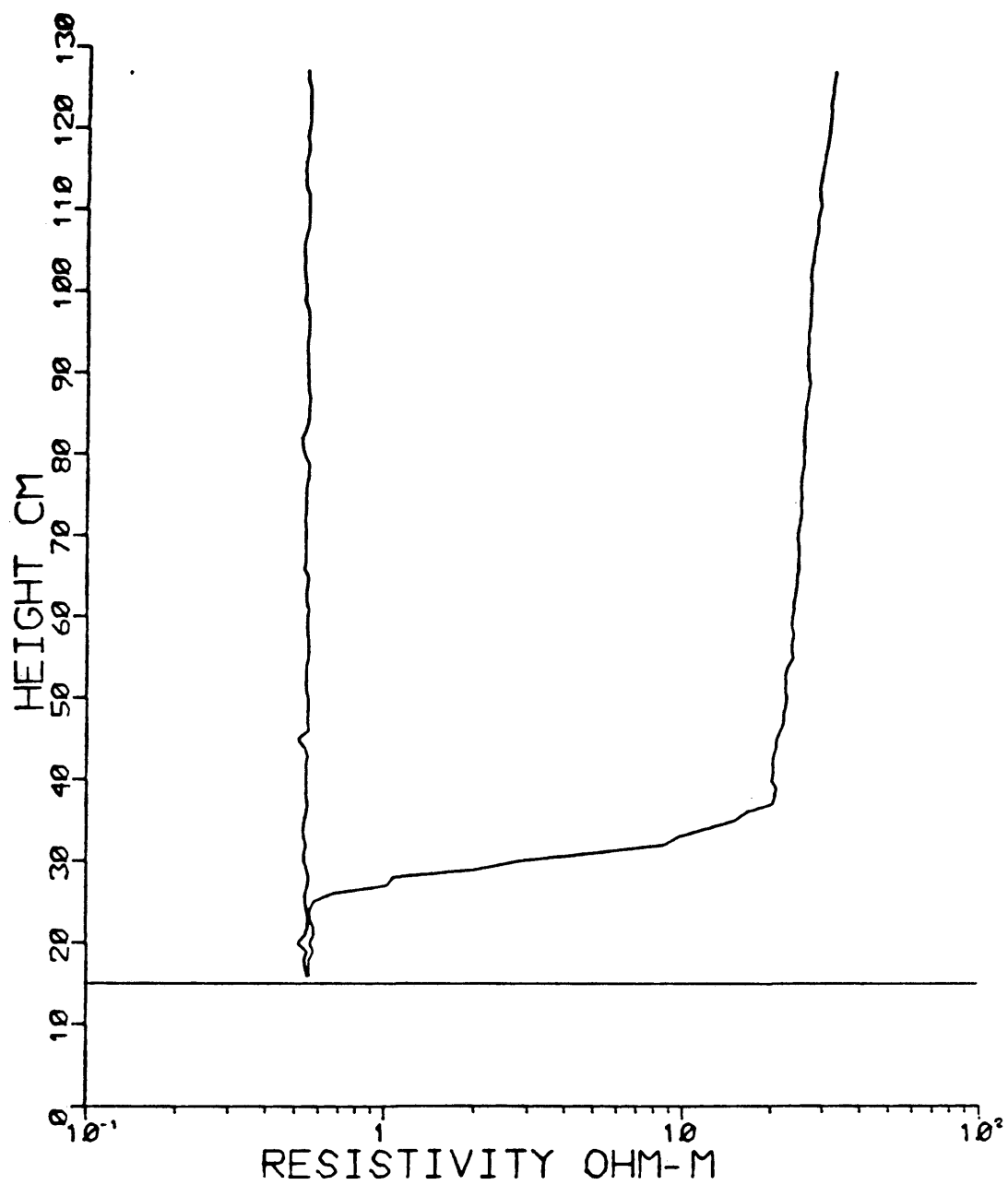


Figure 23. Medium sand column R_0 and two days later R_t values.

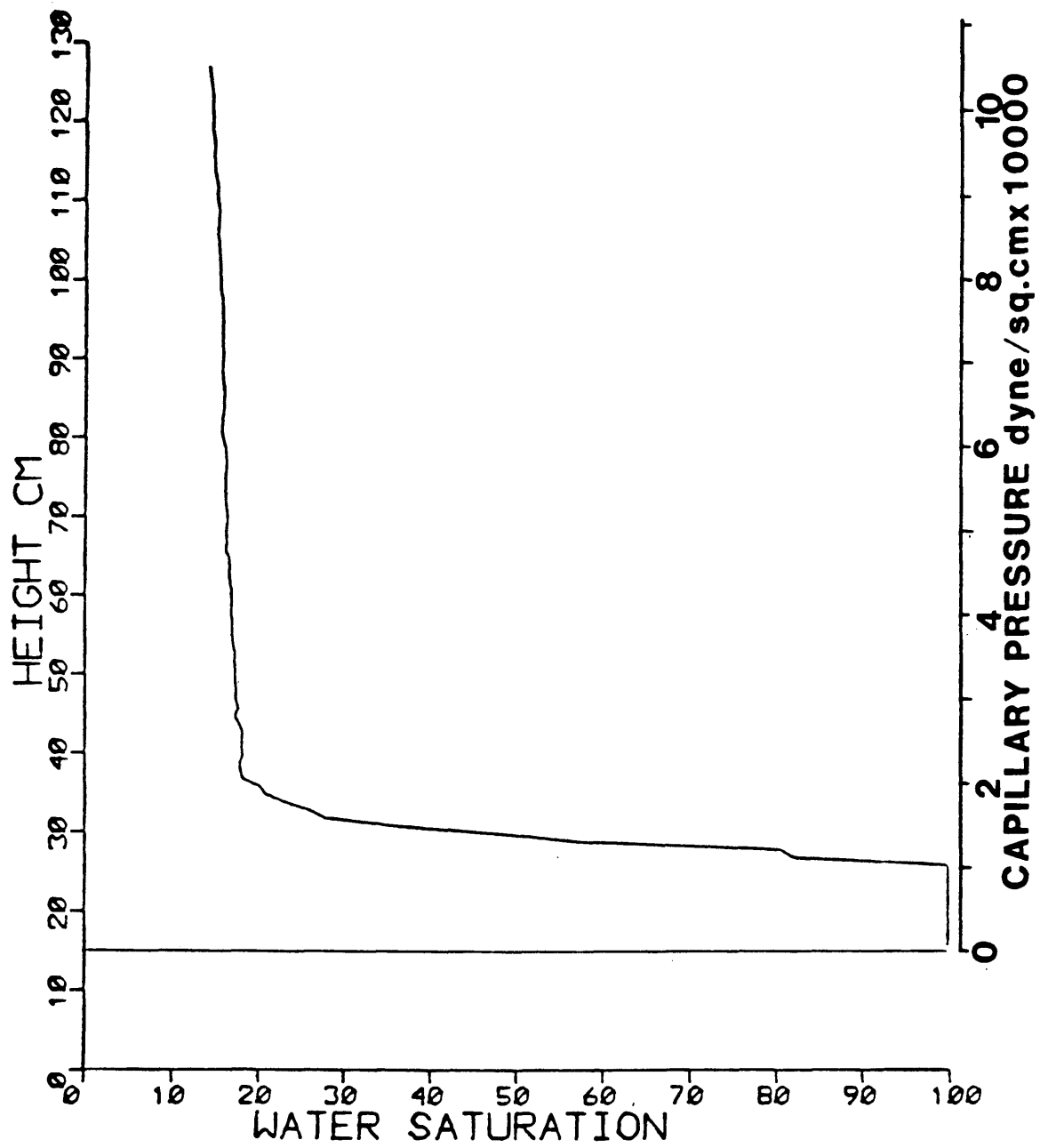


Figure 24. Medium sand column $n = 2.0$, two days later
 S_w vs. P_c .

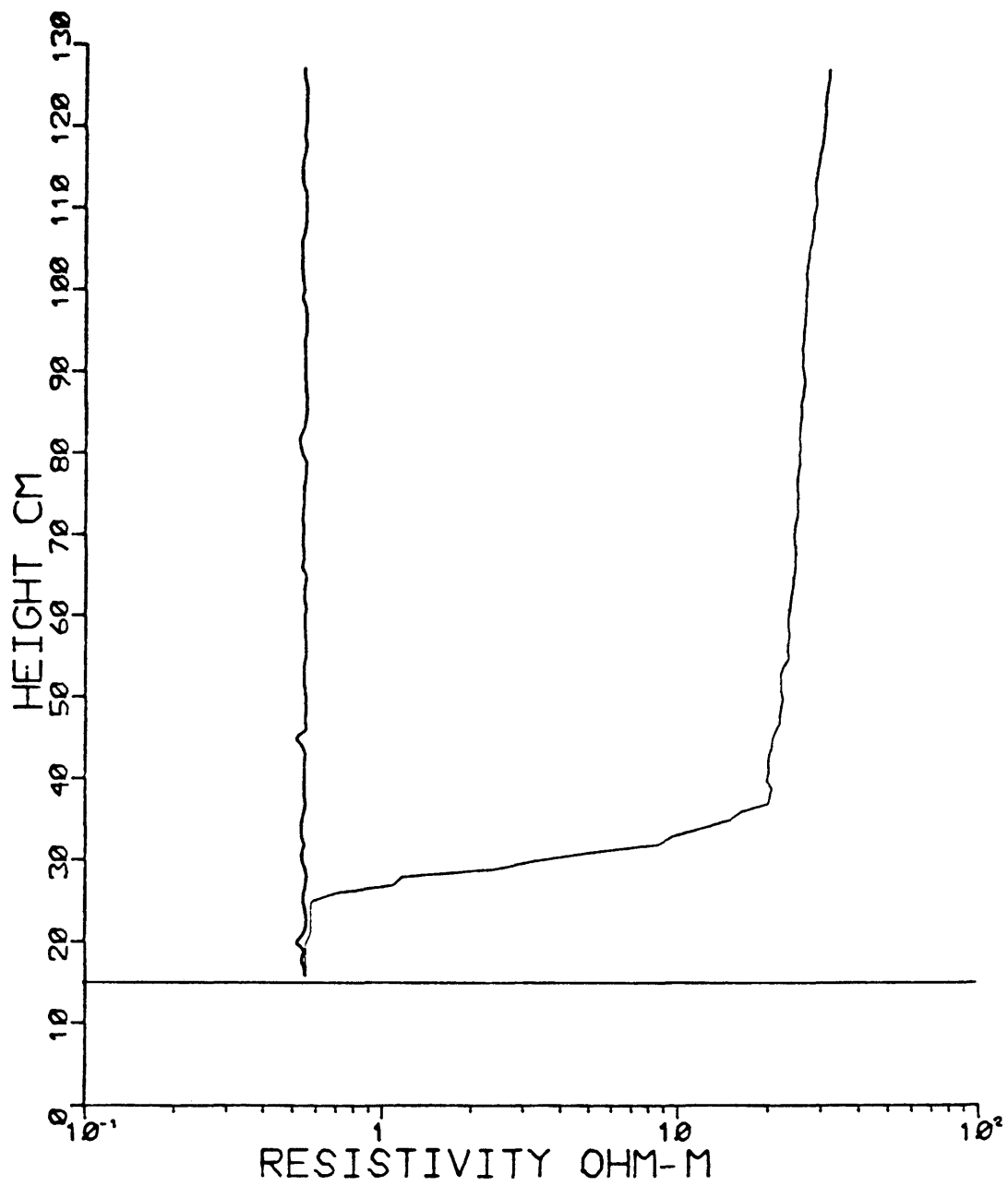


Figure 25. Medium sand column R_o and three days later R_t values.

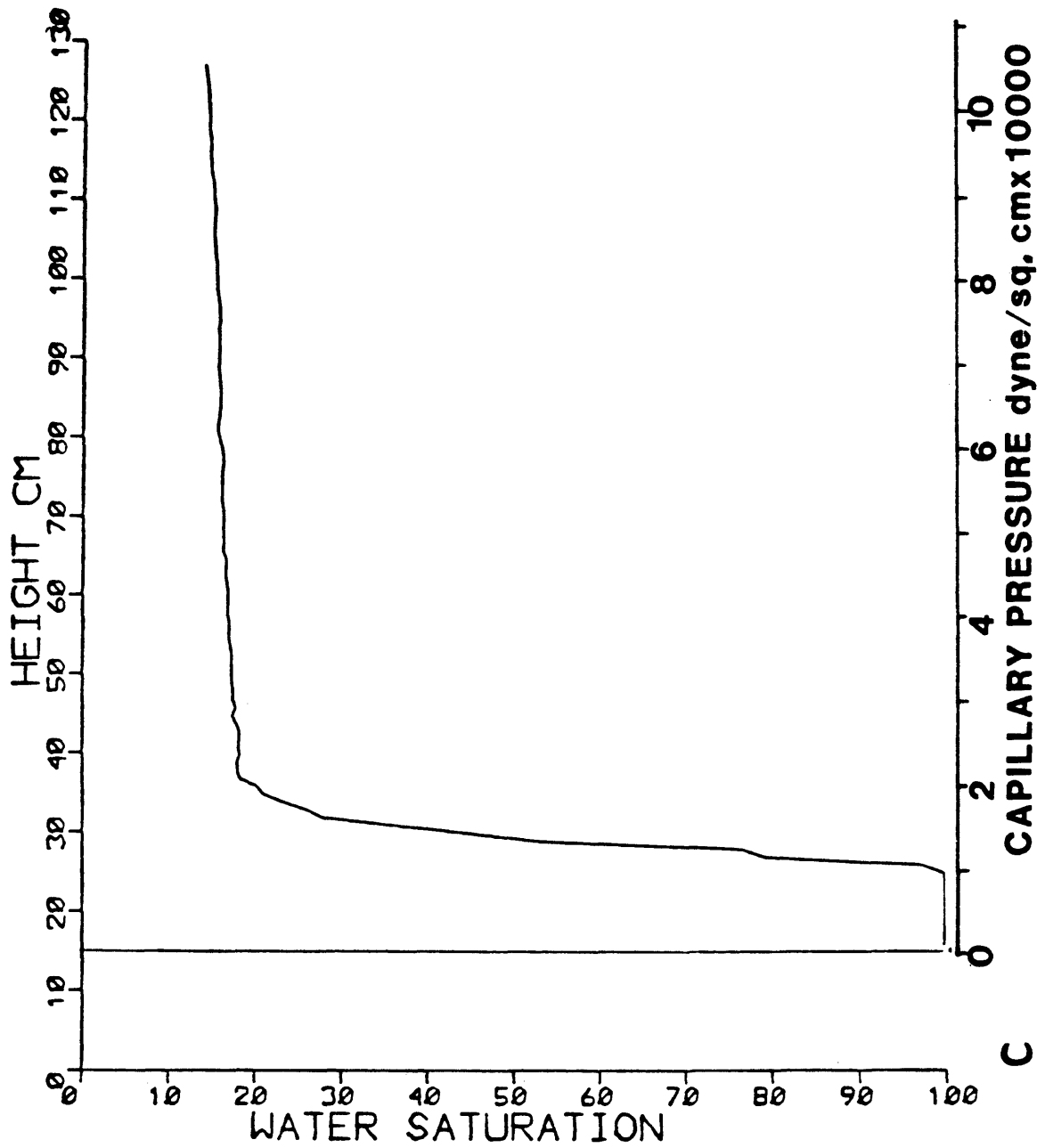


Figure 26. Medium sand column $n = 2.0$, three days later S_w vs. P_c .

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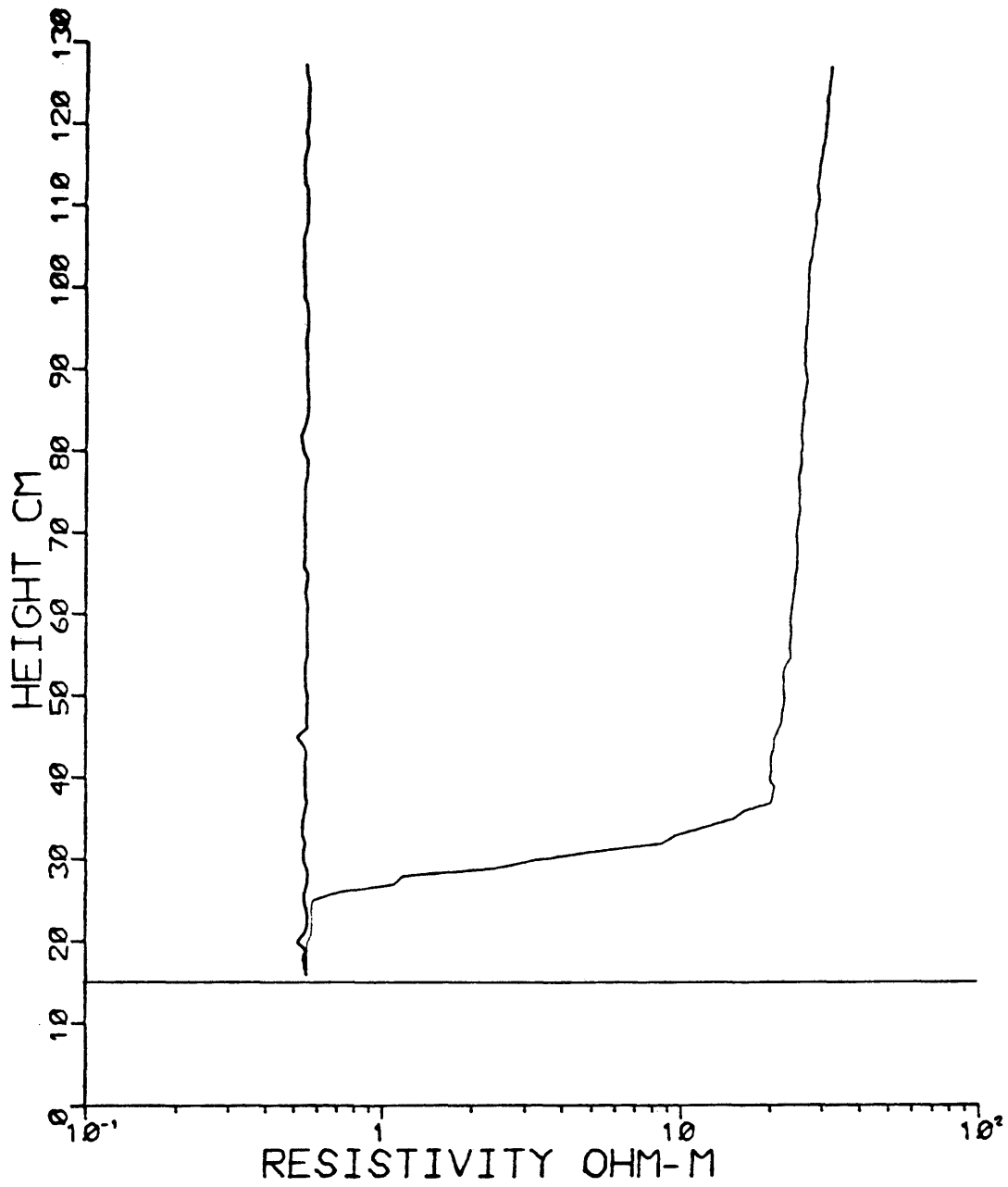


Figure 27. Medium sand column R_o and one week later R_t values.

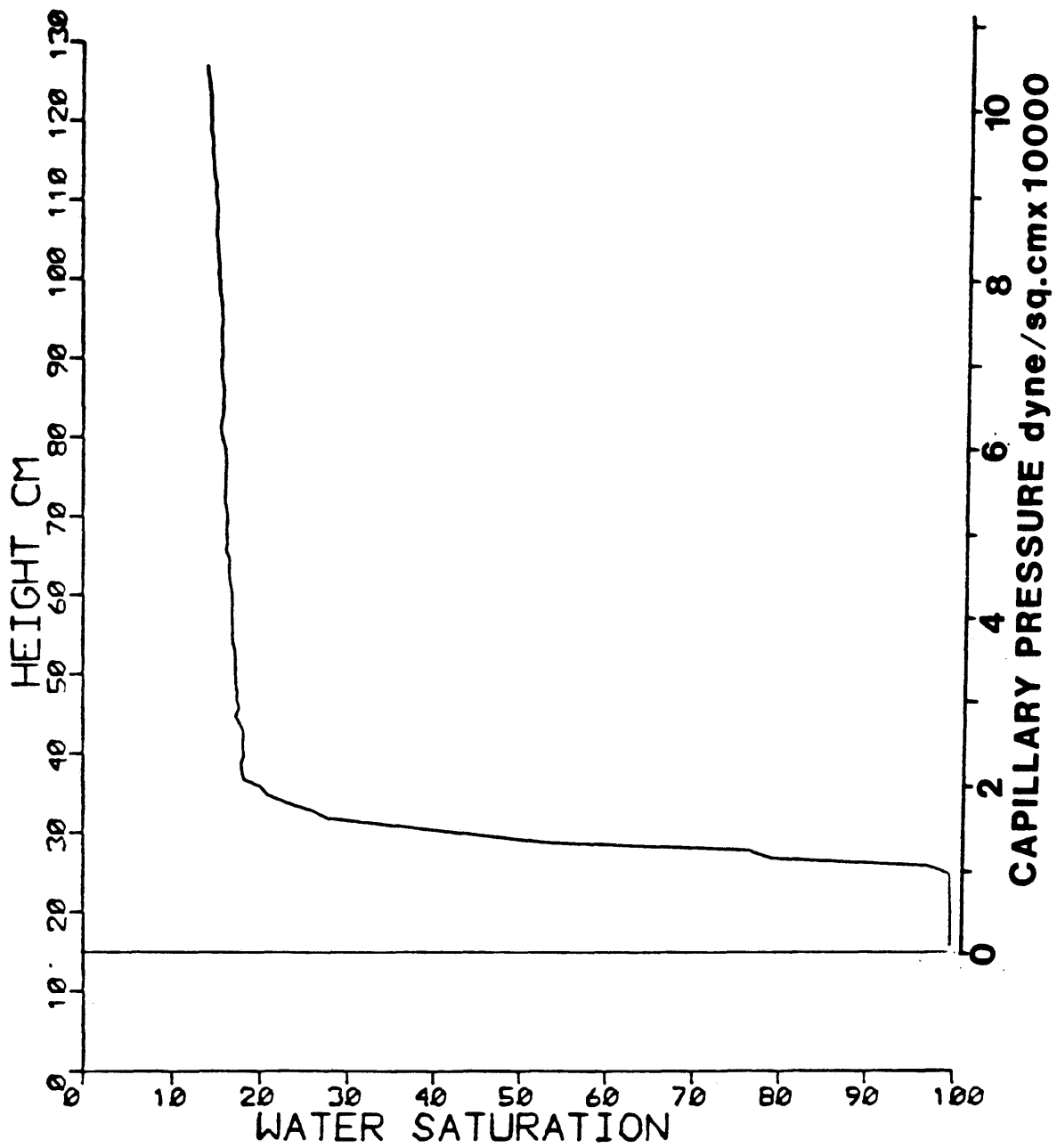


Figure 28. Medium sand column $n = 2.0$, one week later
 S_w vs. P_c .

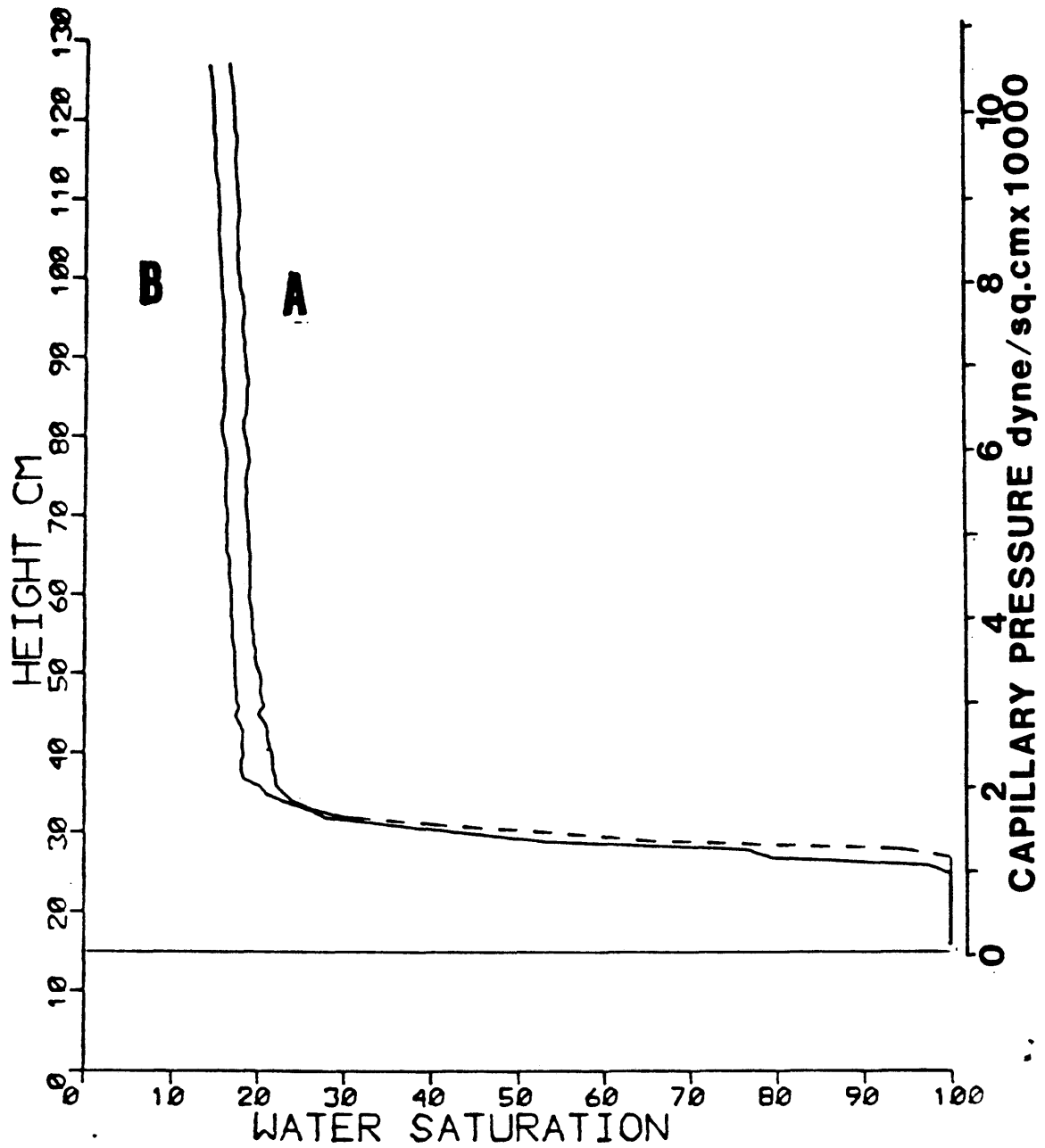


Figure 29. Medium sand column - correlation of S_w - P_c curves; A-one day later, B-one week later.

Fine Sand Column

This time the column was filled with the 100 mesh fine sand. Resistivity measurements were first carried out when the column was 100% brine saturated. Later, the valve at the bottom of the column was opened, and the column was allowed to reach its equilibrium. It was observed that this was a very slow process for the fine sand compared to the two previous cases. Again, R_o values were a vertical line as was expected (Figure 30). As is shown in Figures 31 through 33, even after two days there is a considerable amount of change. Particularly, Figure 33 shows that the S_w vs. height curve is quite noisy. This is a sign that the column has not reached its capillary equilibrium. However, one day later, after three days total delay the S_w vs. height curve was much smoother. In fact, after three days no water came out of column. Figures 31 through 36 show the changes on the R_t and S_w curves after two days, three days and one week delay.

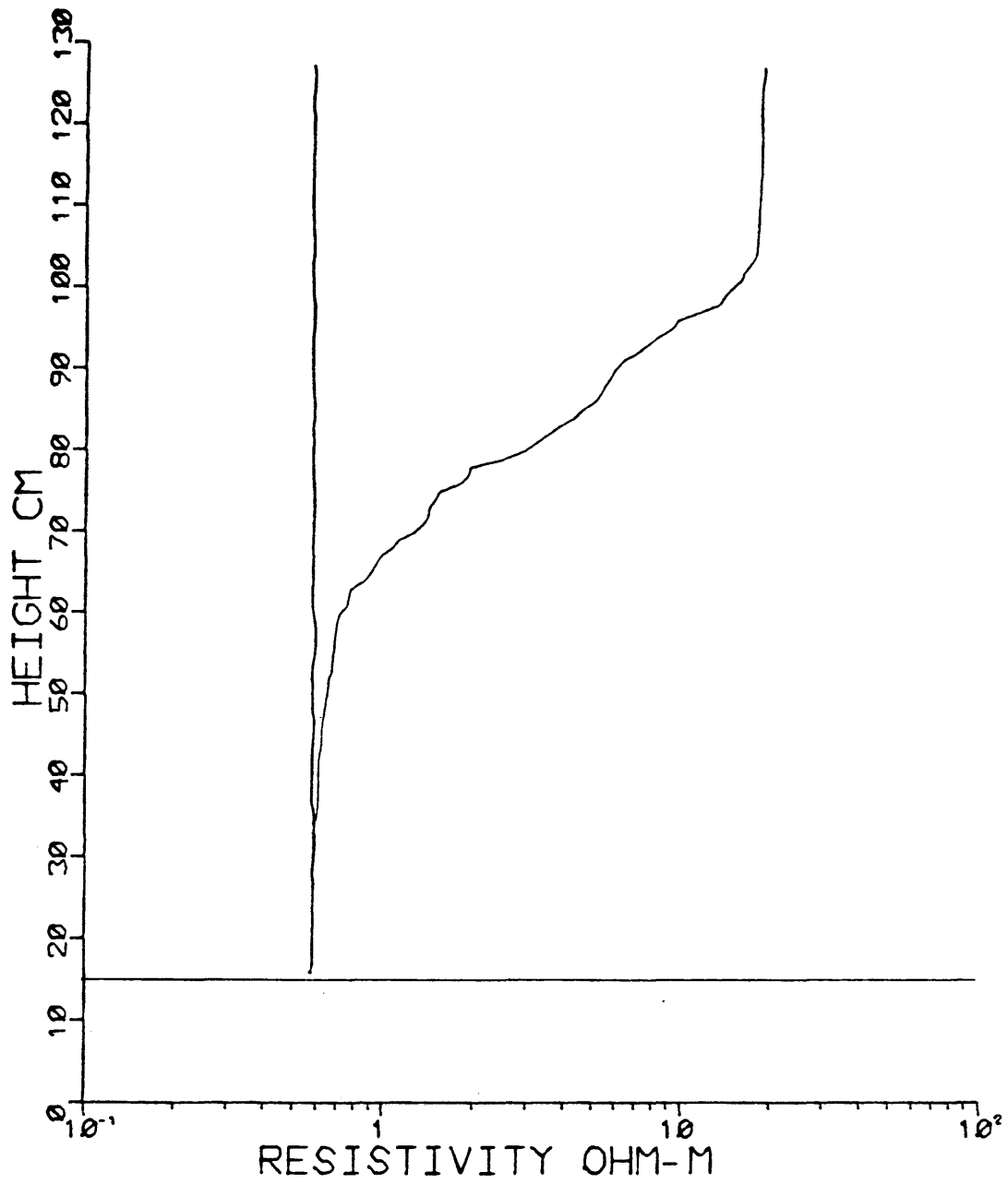


Figure 30. Fine sand column R_o and one day later R_t values.

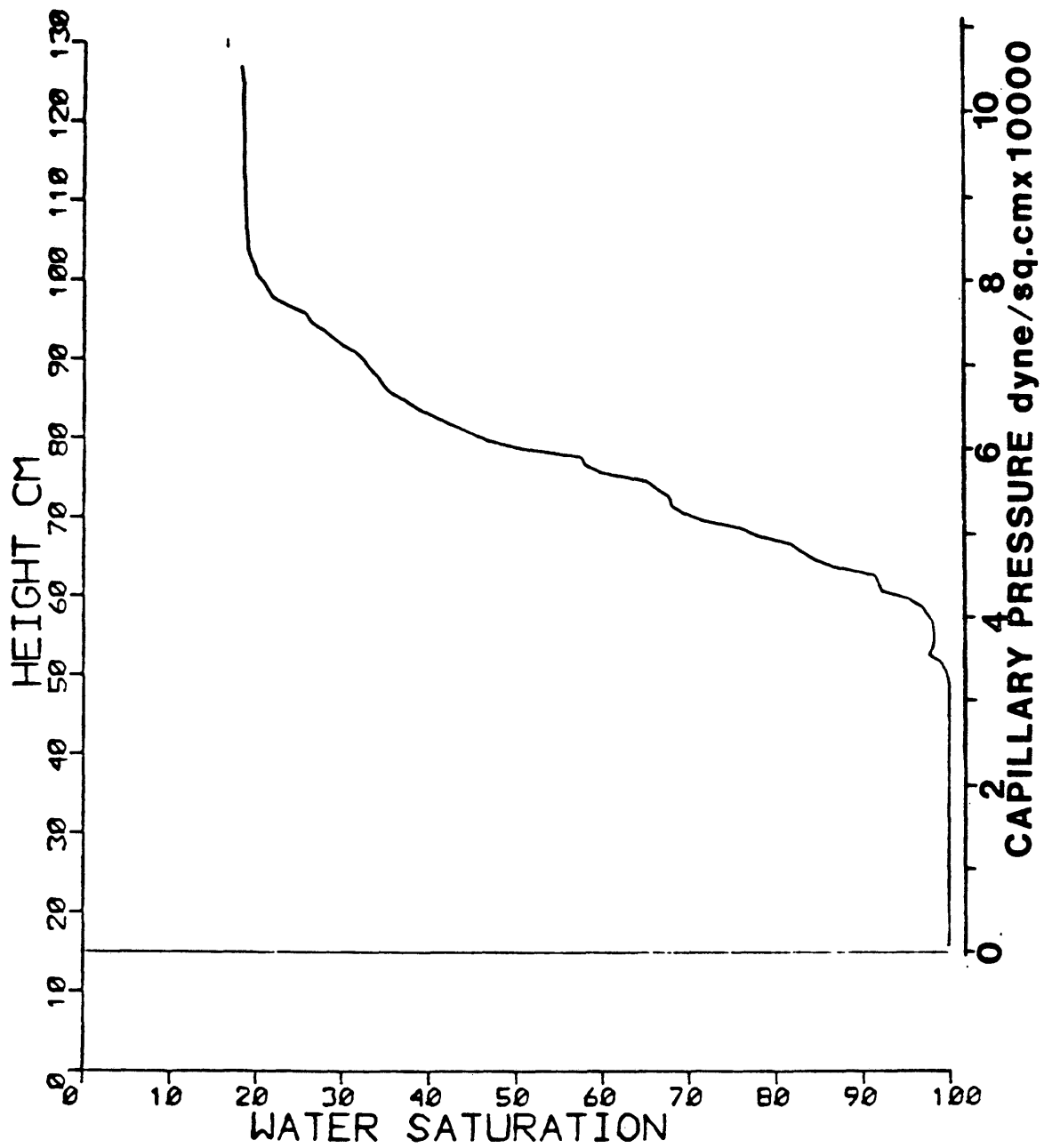


Figure 31. Fine sand column $n = 2.0$, one day later
 S_w vs. P_c .

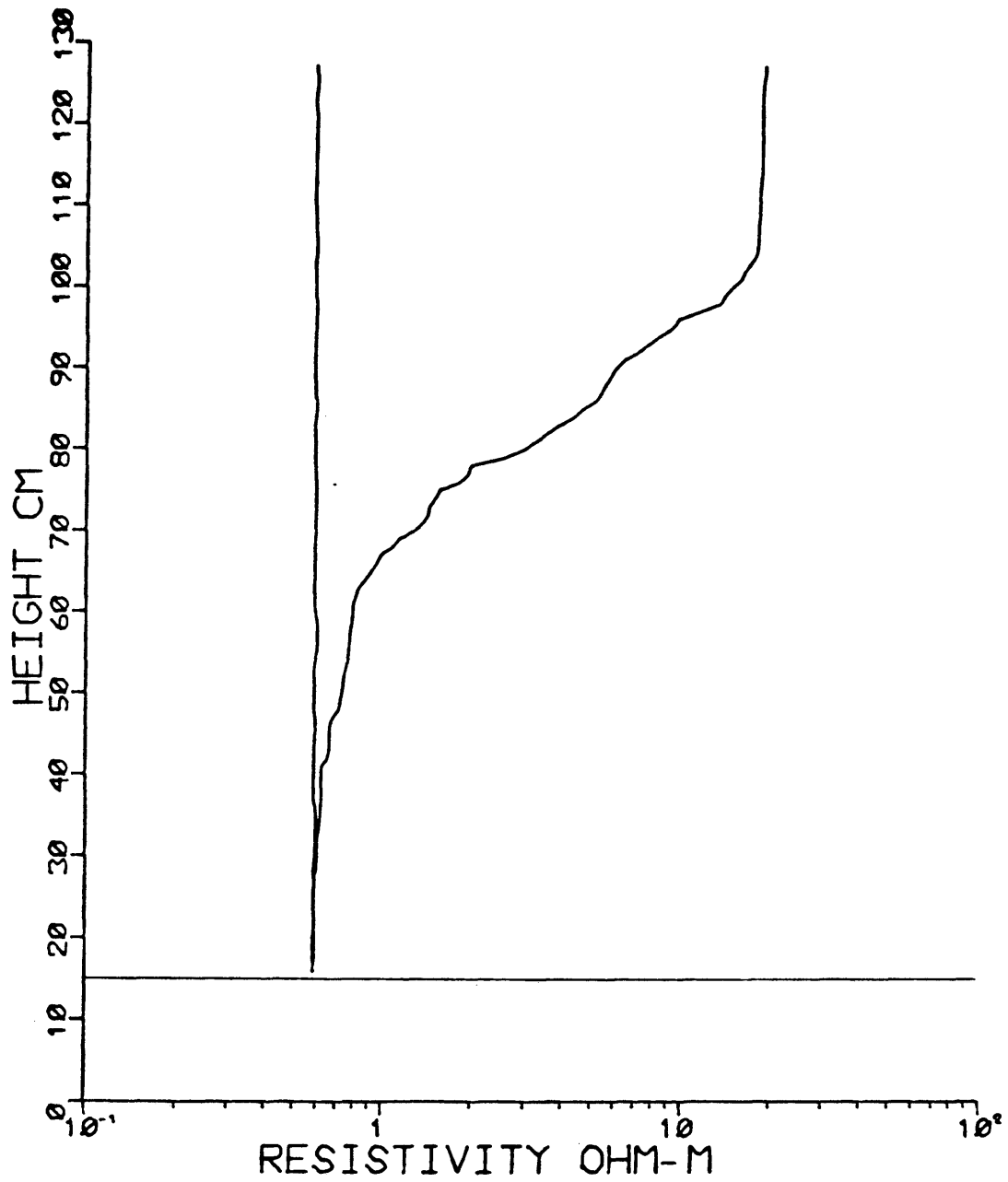


Figure 32. Fine sand column R_0 and two days later R_t values.

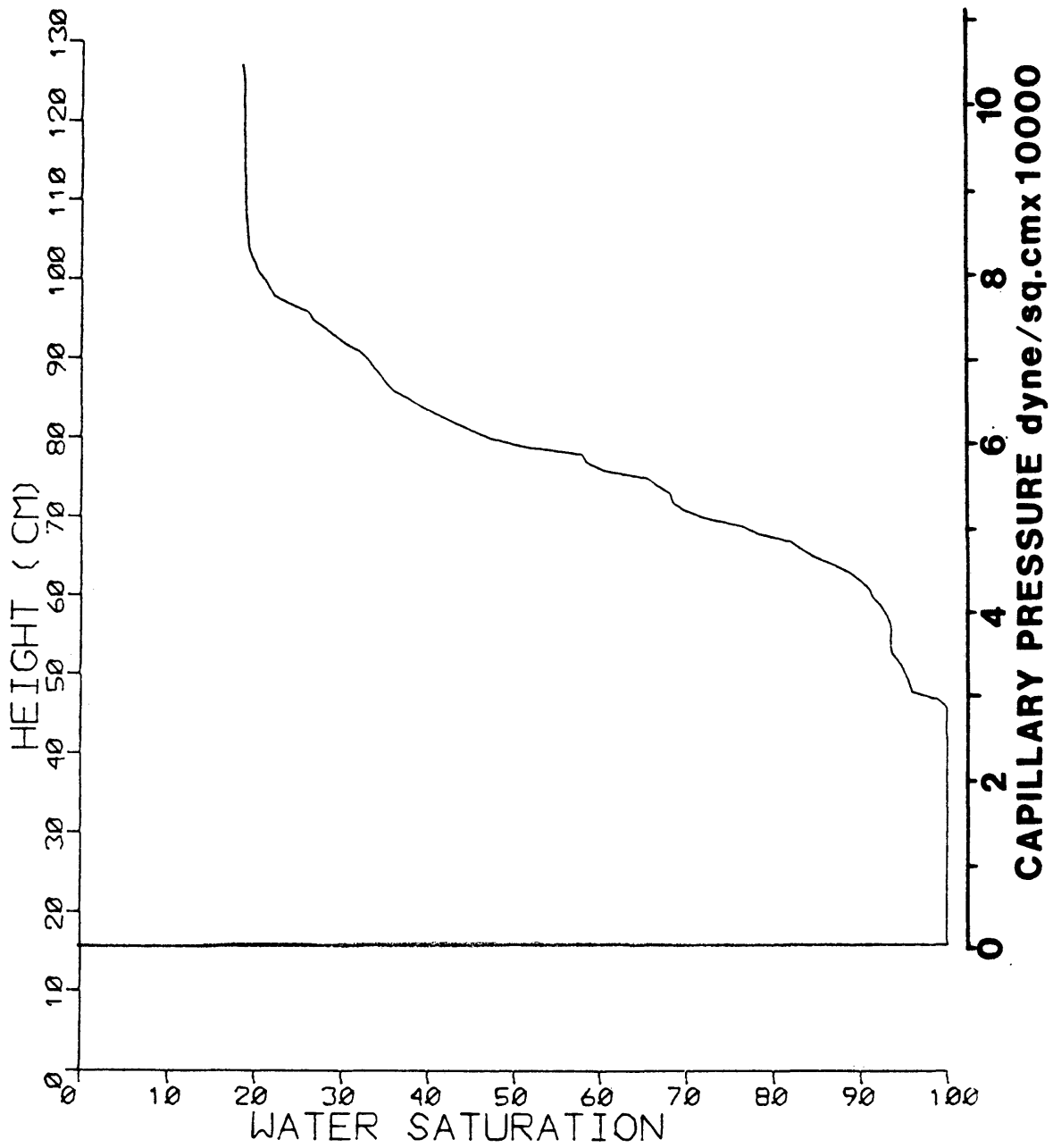


Figure 33. Fine sand column $n = 2.0$, two days later
 S_w vs. P_c .

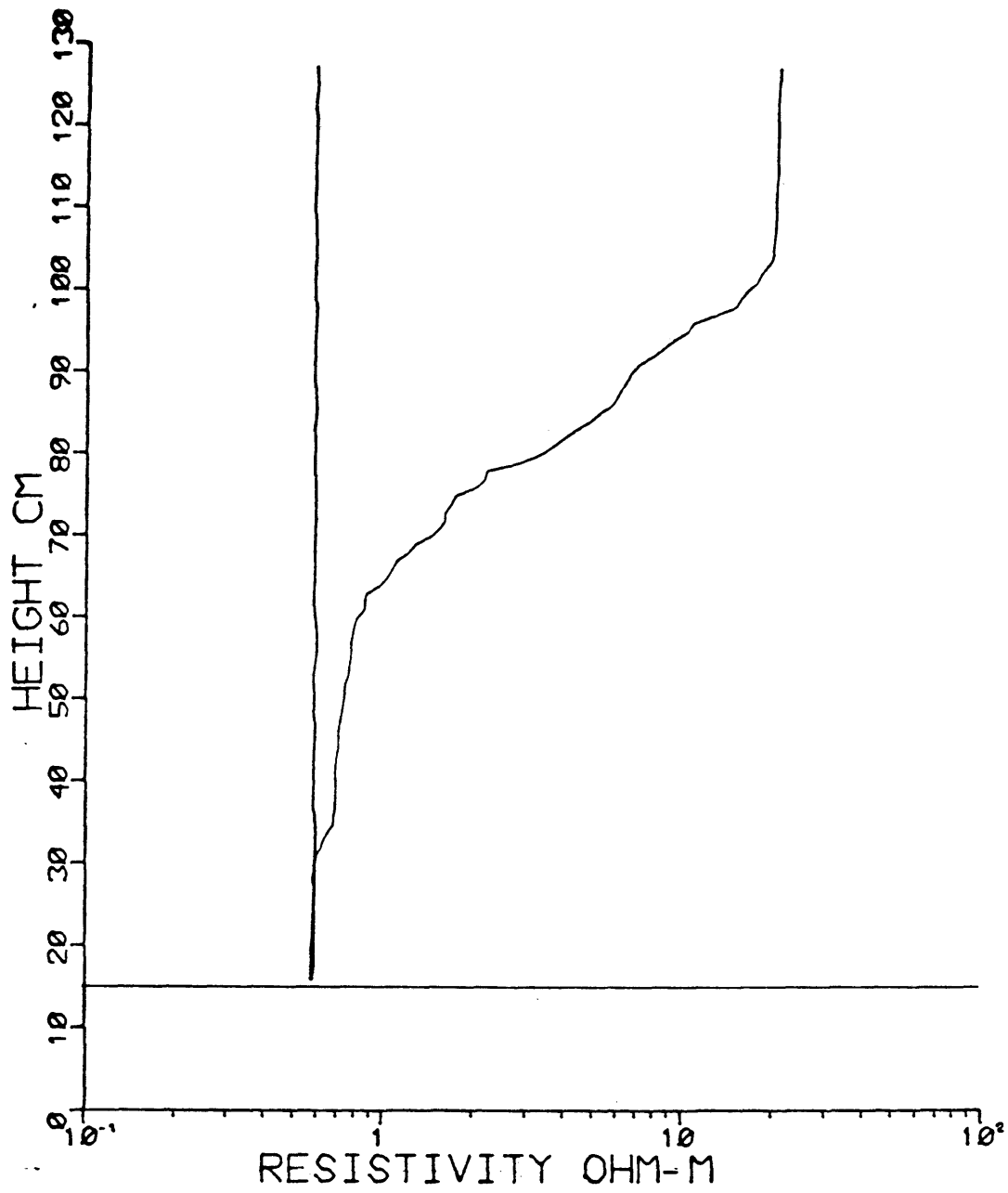


Figure 34. Fine sand column R_o and three days later R_t values.

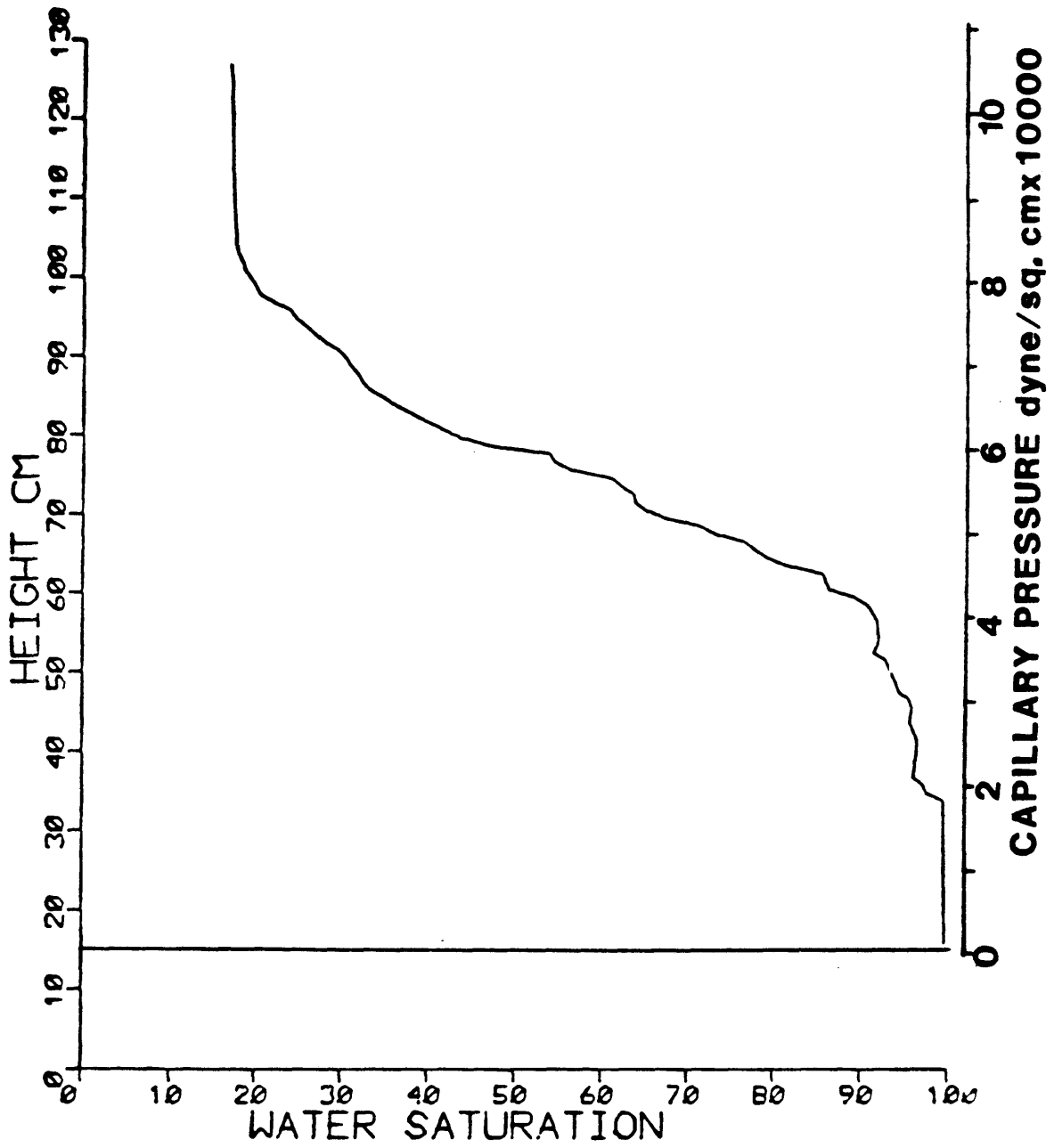


Figure 35. Fine sand column $n = 2.0$, three days later S_w vs. P_c .

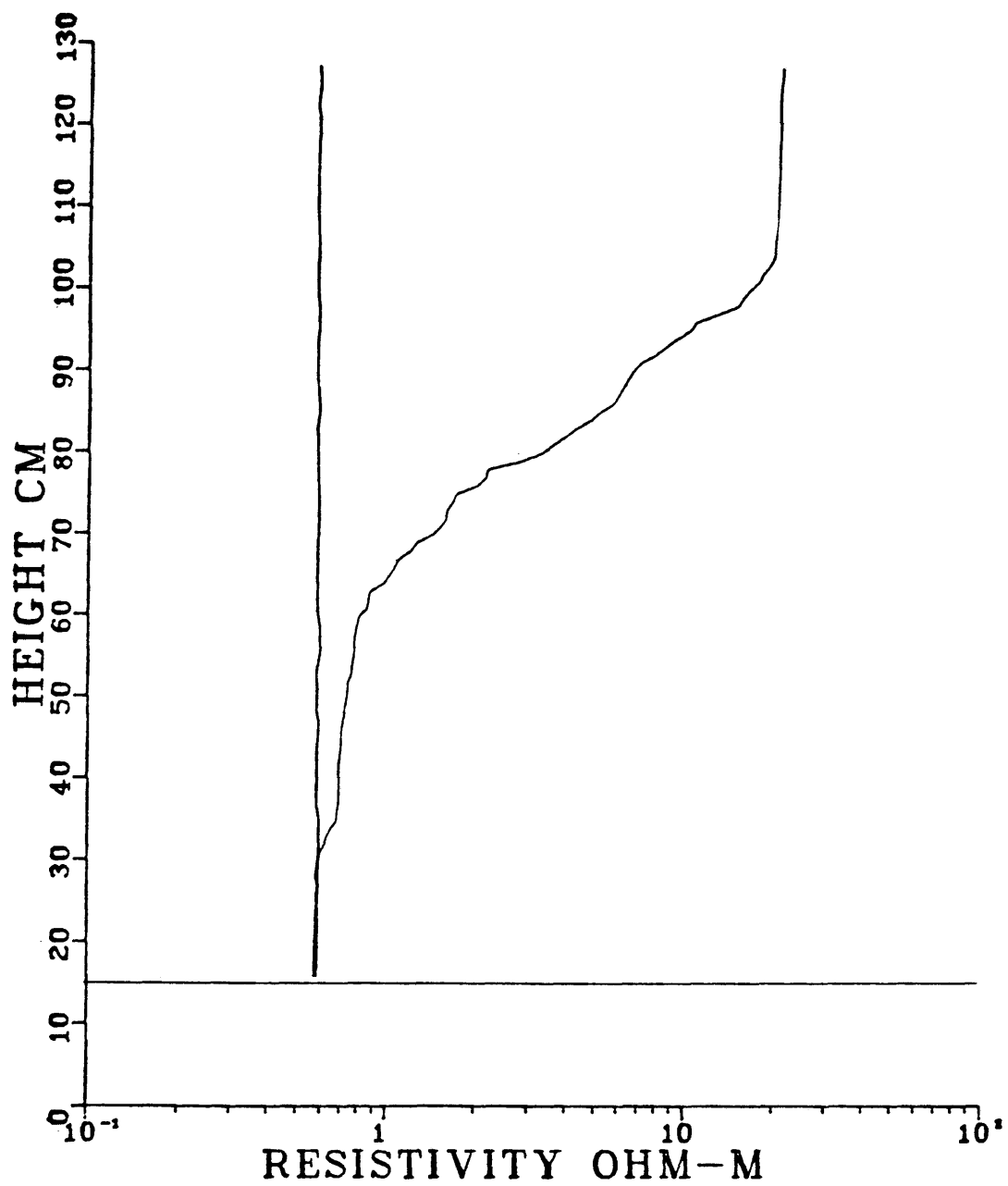


Figure 36. Fine sand column R_o and one week later R_t values.

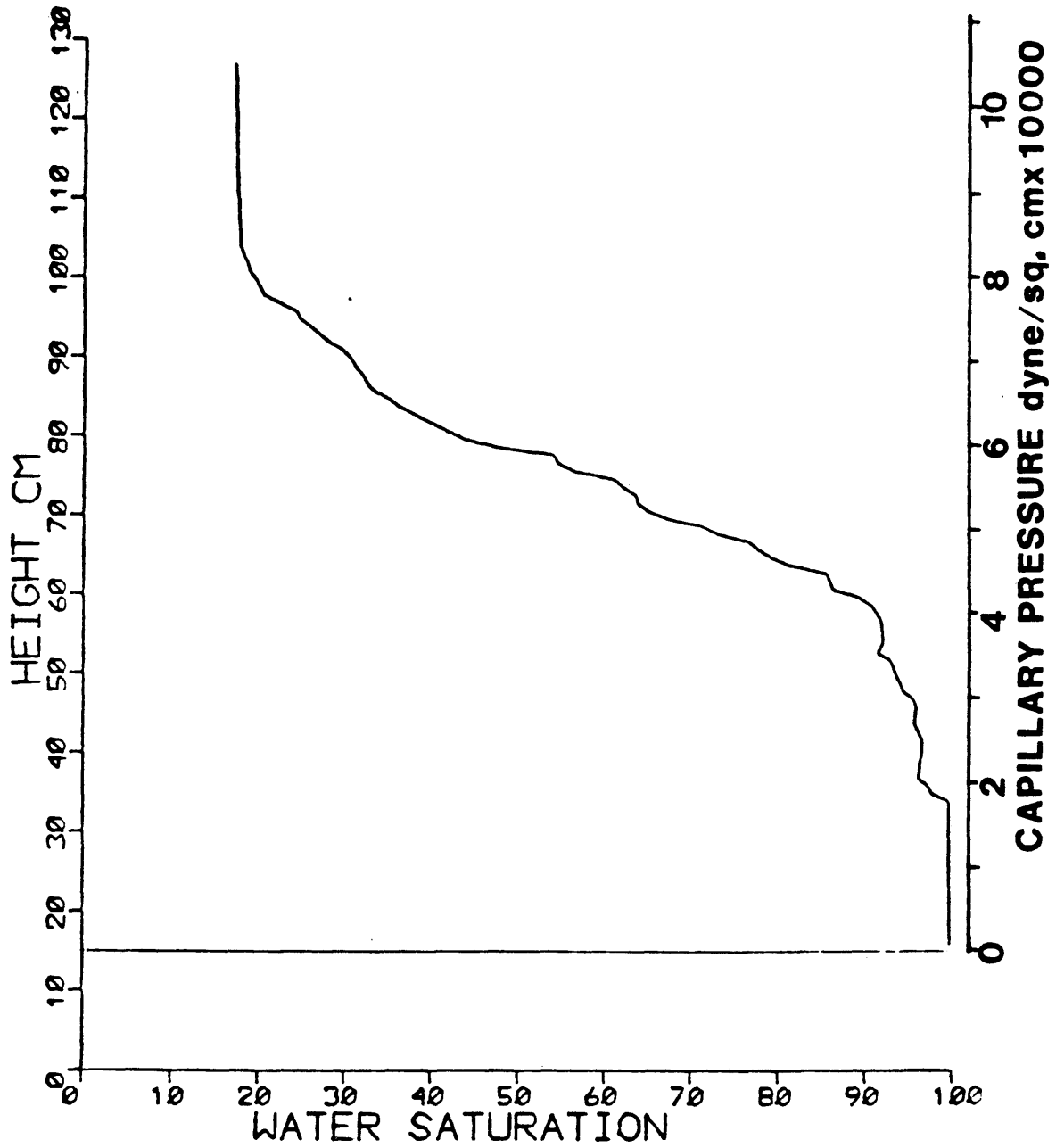


Figure 37. Fine sand column $n = 2.0$, one week later
 S_w vs. P_c .

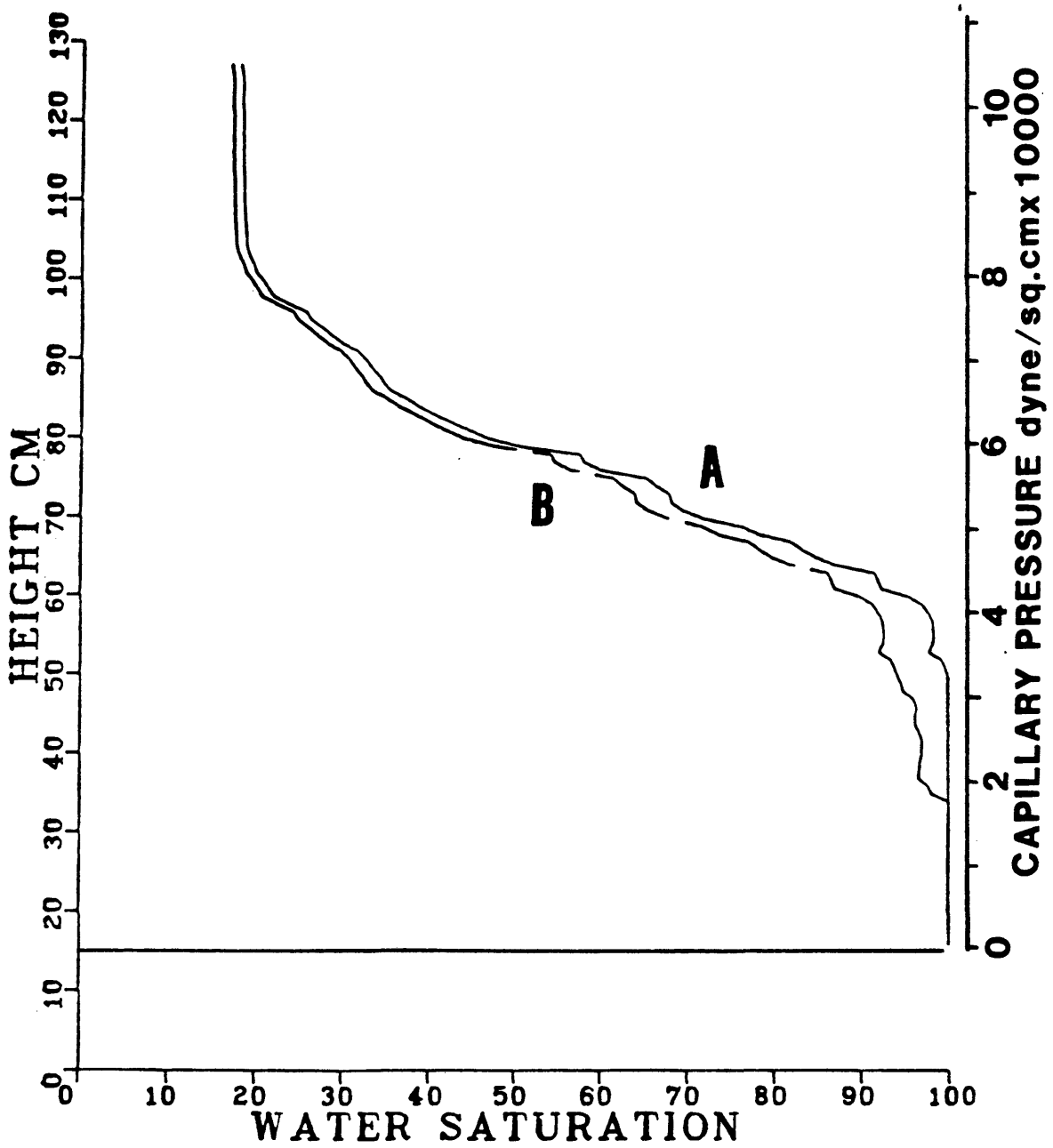


Figure 38. Fine sand column - correlation of S_w - P_c curves; A-one day later, B-one week later.

Layered Sand Column

One of the important purposes of this study was to determine how capillary pressure would change when the column was a layered medium. A layered column of three different size sand grains was prepared (see Figure 39). Layers were separated by paper coffee filter to prevent one sand from flowing into the other. First, resistivity measurements were carried out for R_o values when the column was 100% brine saturated. Later the valve at the bottom of the column was opened, and the column was left to reach its capillary equilibrium. As is shown in Figure 40, R_o for the column gives very nice contrast between the layers. It was observed that the process of reaching capillary equilibrium for this column was very slow, just like for the fine sand column. Even after three days some changes were observed. In Figures 40 through 46 these changes can be seen.

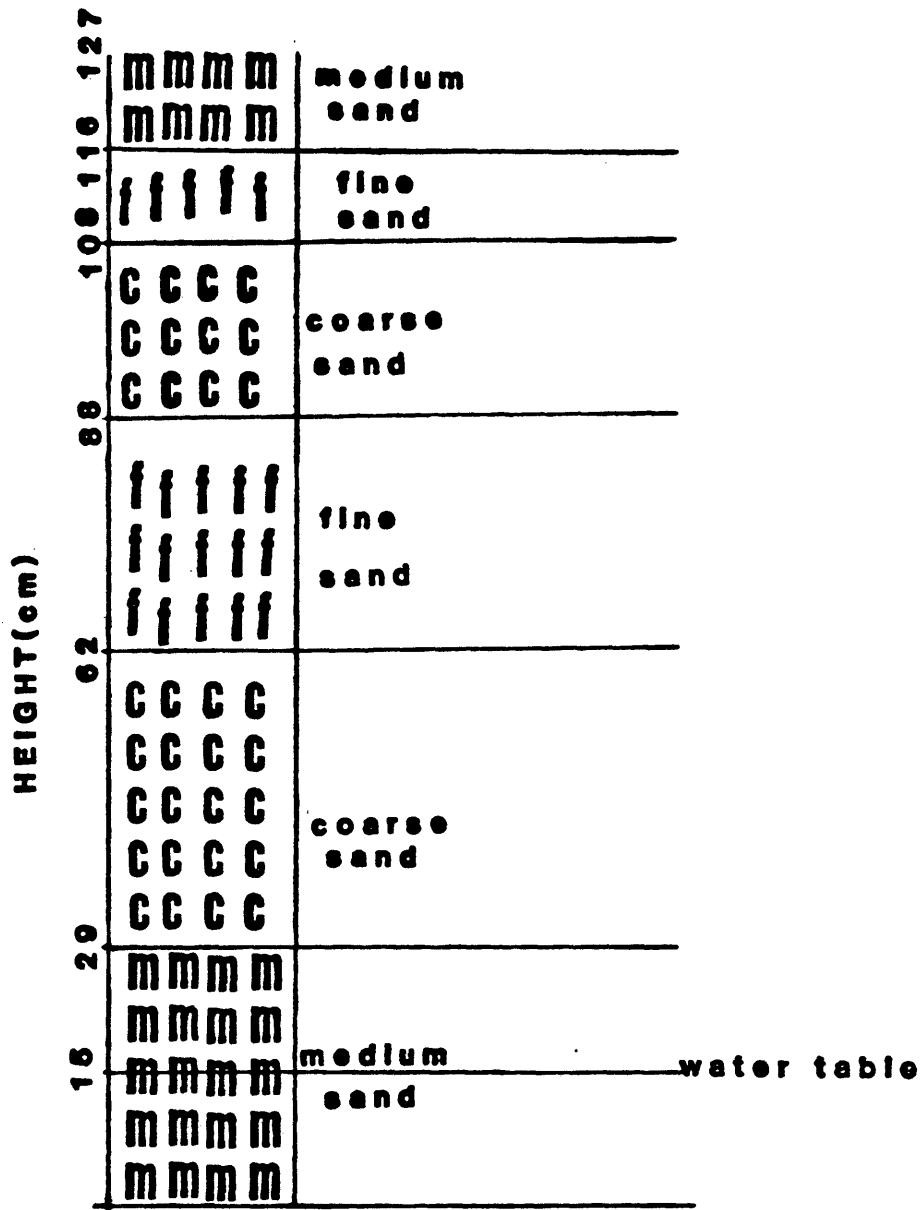


Figure 39. Layered sand column.

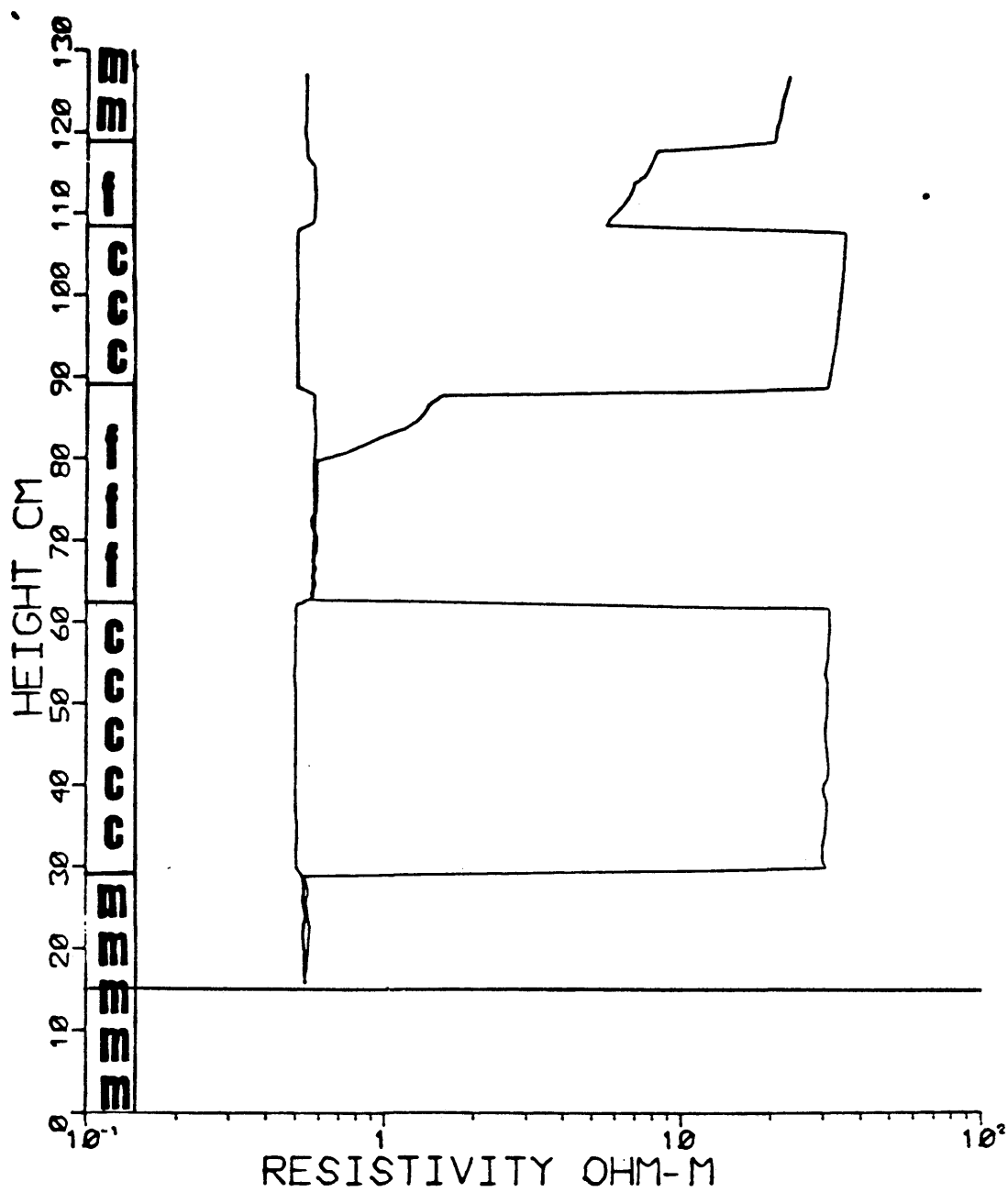


Figure 40. Layered sand column R_0 and one day later R_t values.

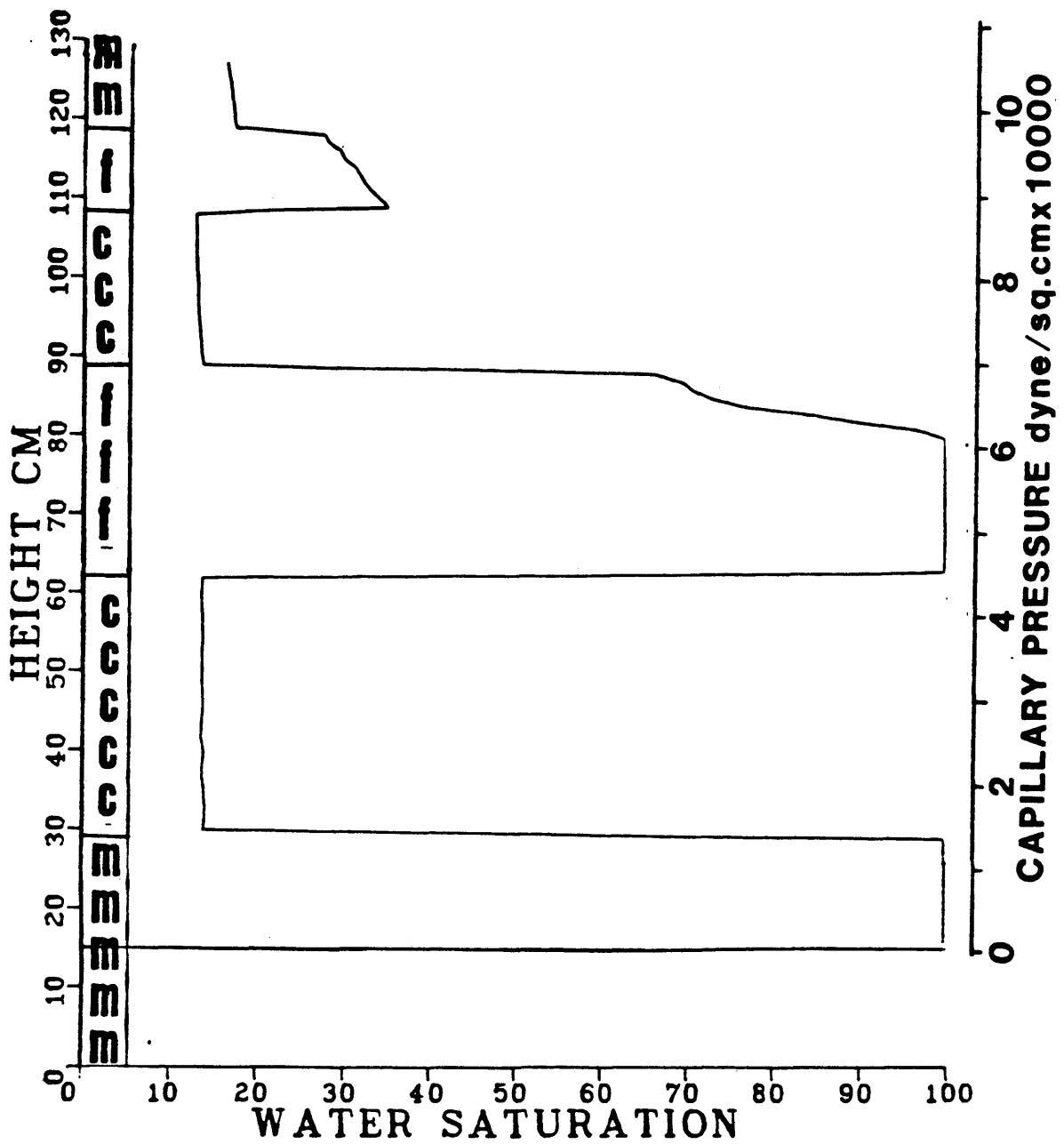


Figure 41. Layered sand column $n = 2.0$, one day later S_w vs. P_c .

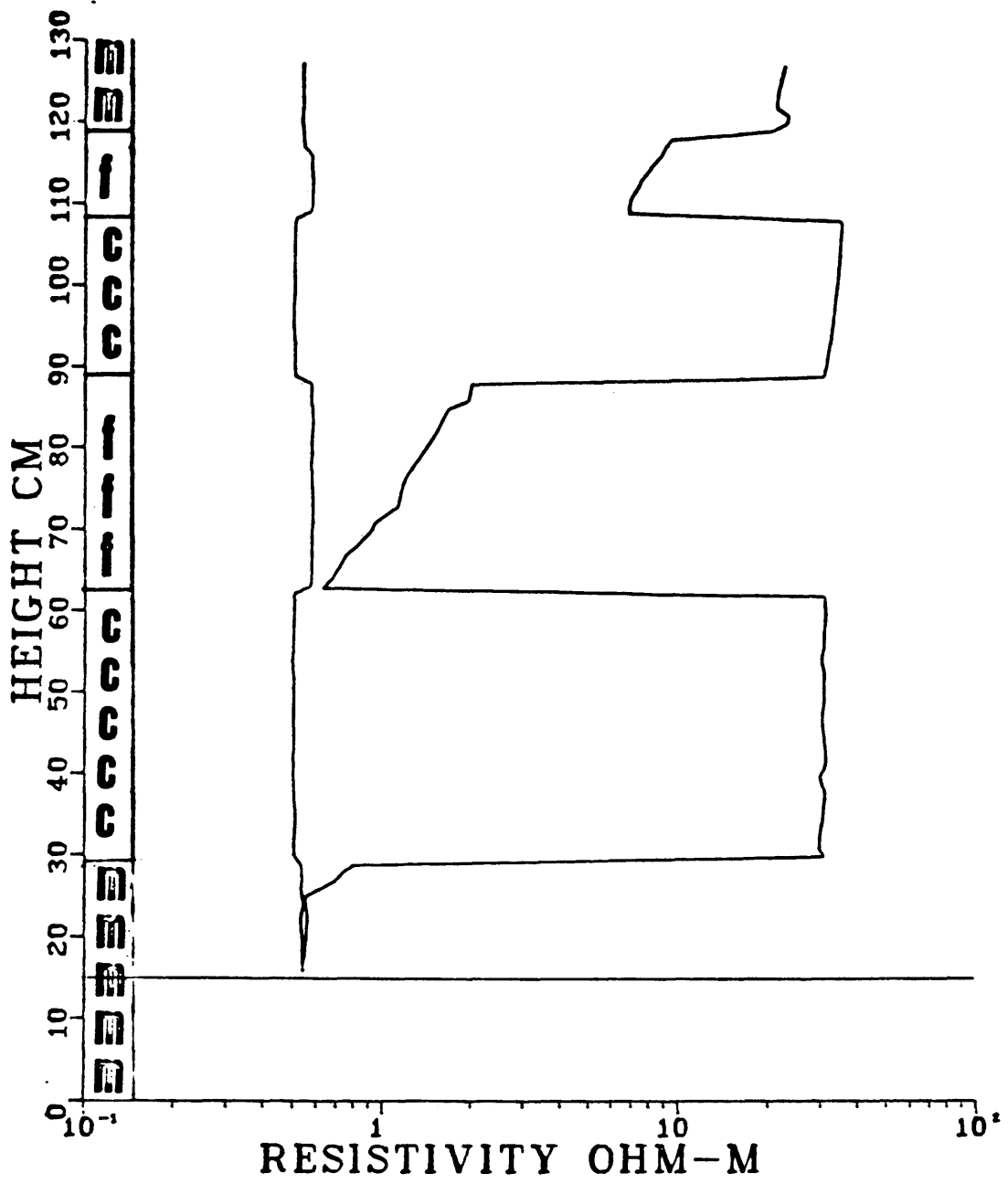


Figure 42. Layered sand column R_0 and two days later R_t values.

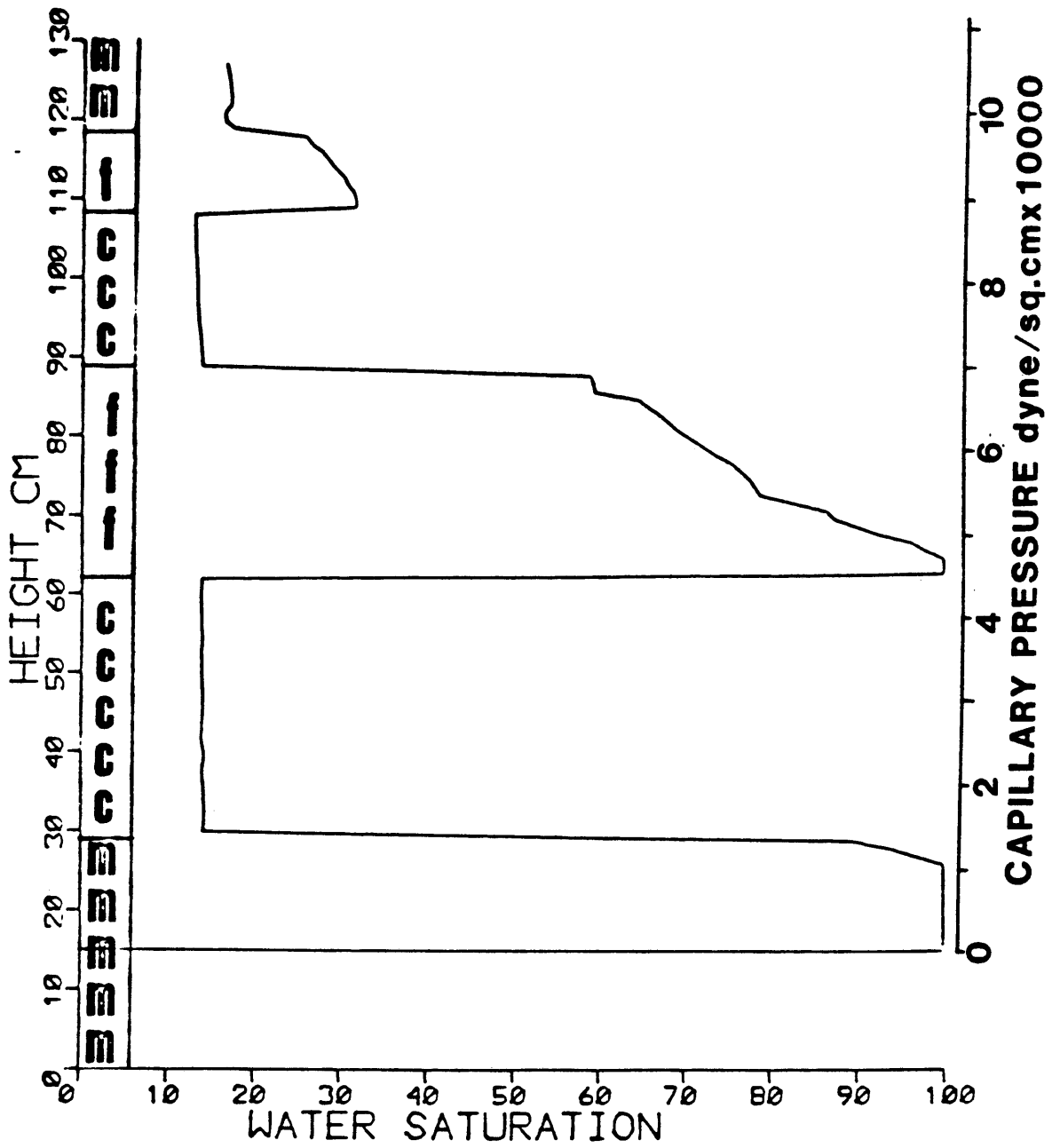


Figure 43. Layered sand column $n = 2.0$, two days later S_w vs. P_c .

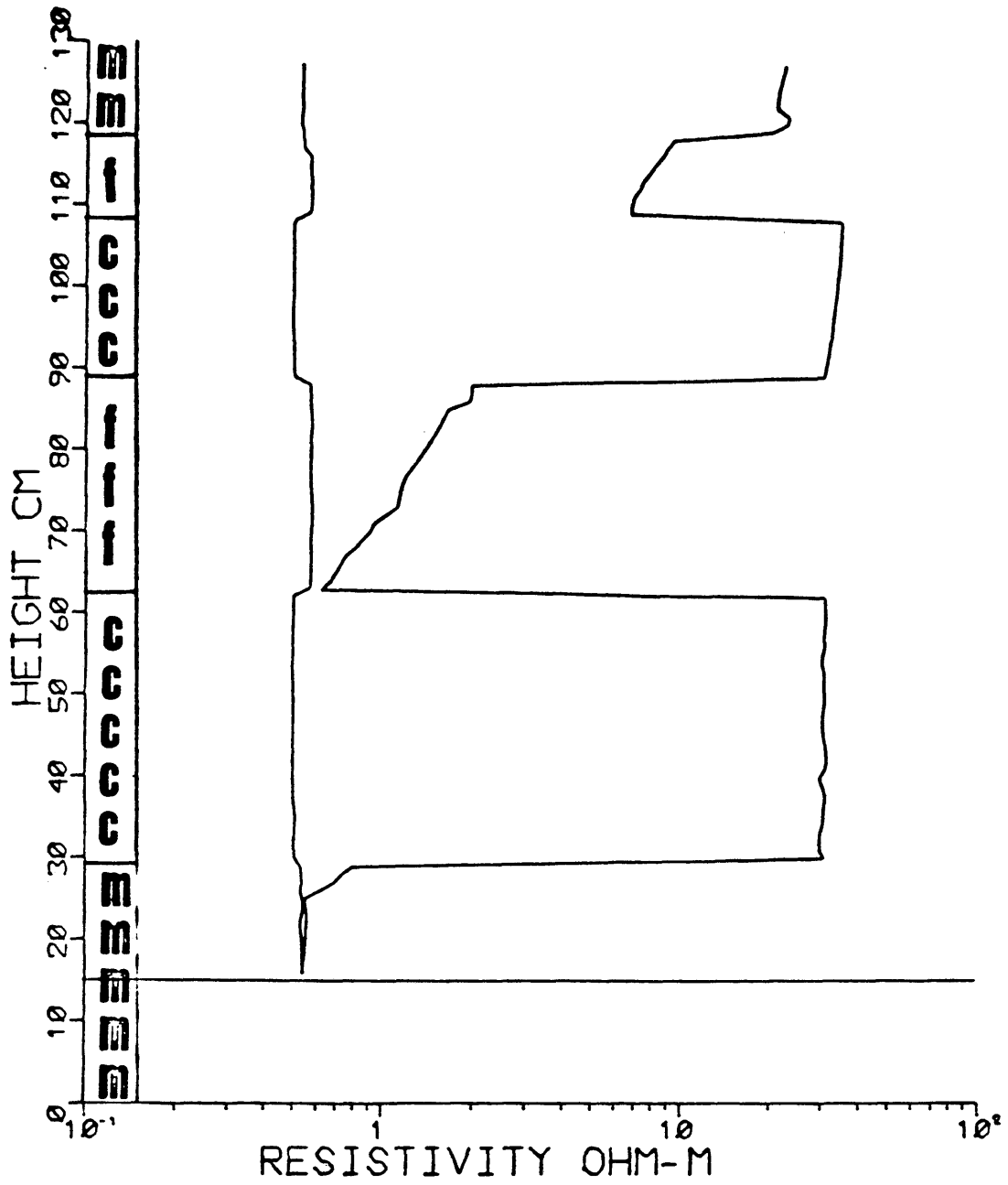


Figure 44. Layered sand column R_0 and three days later R_t values.

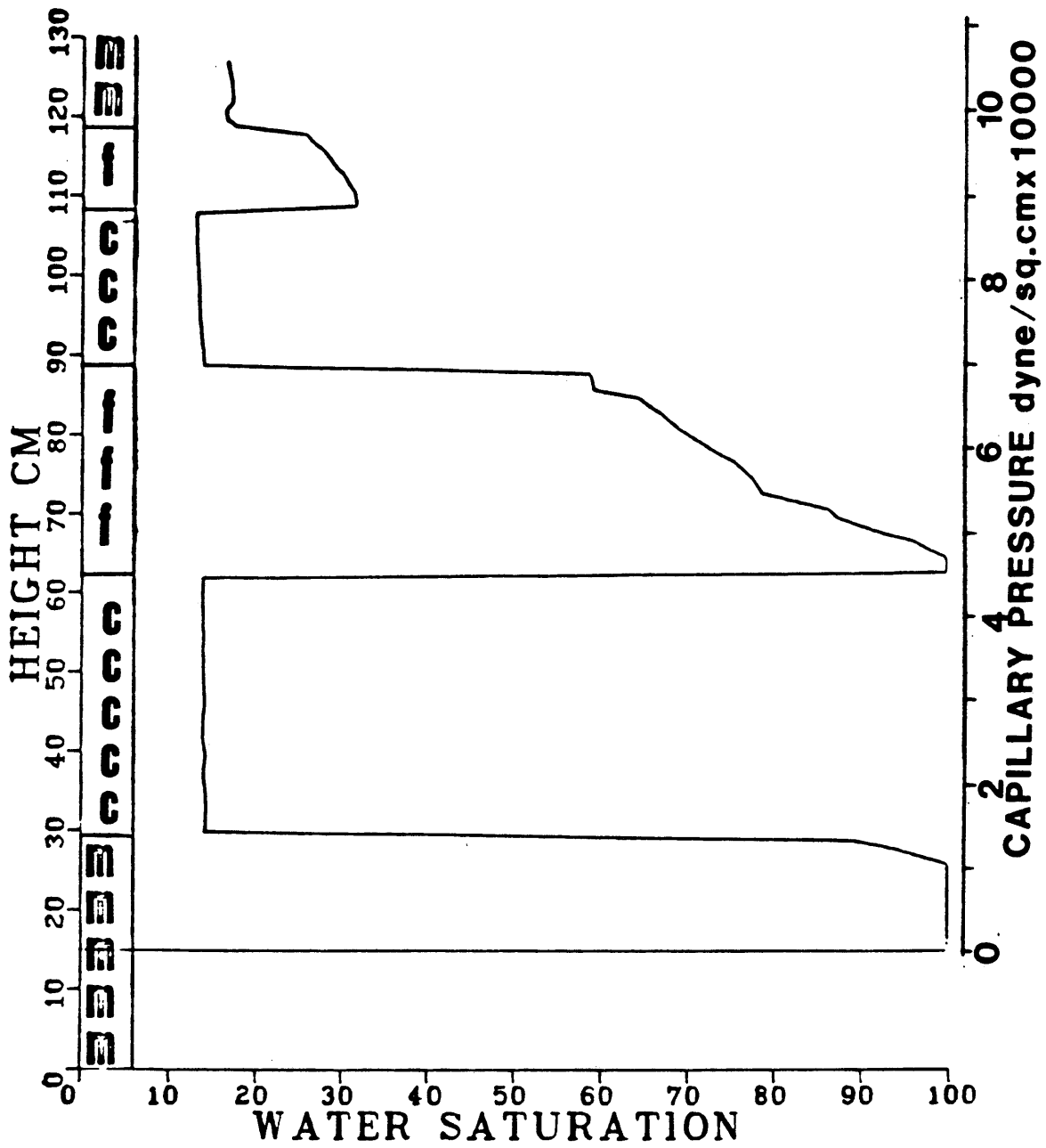


Figure 45. Layered sand column $n = 2.0$, three days later S_w vs. P_c .

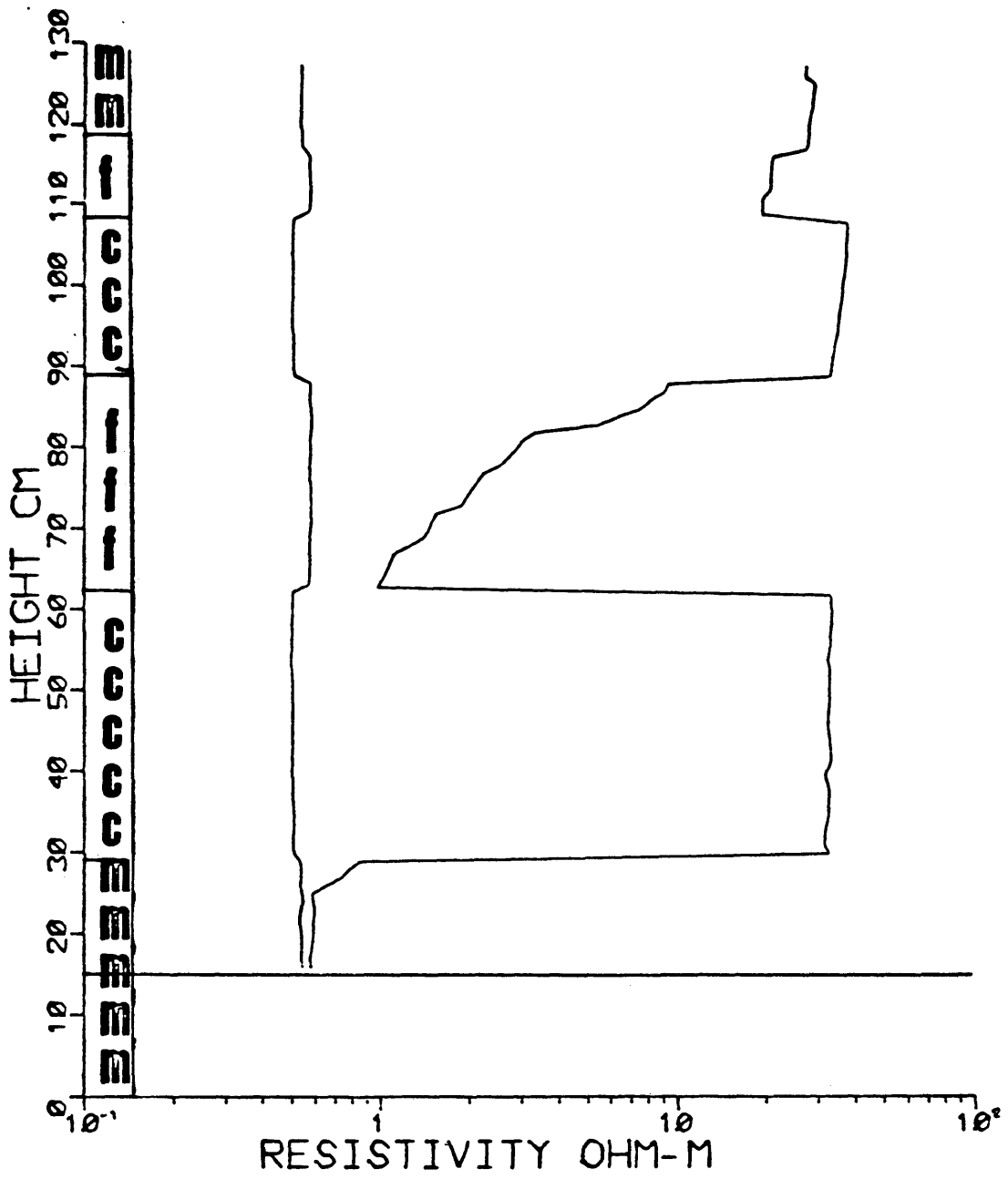


Figure 46. Layered sand column R_0 and one week later R_t values.

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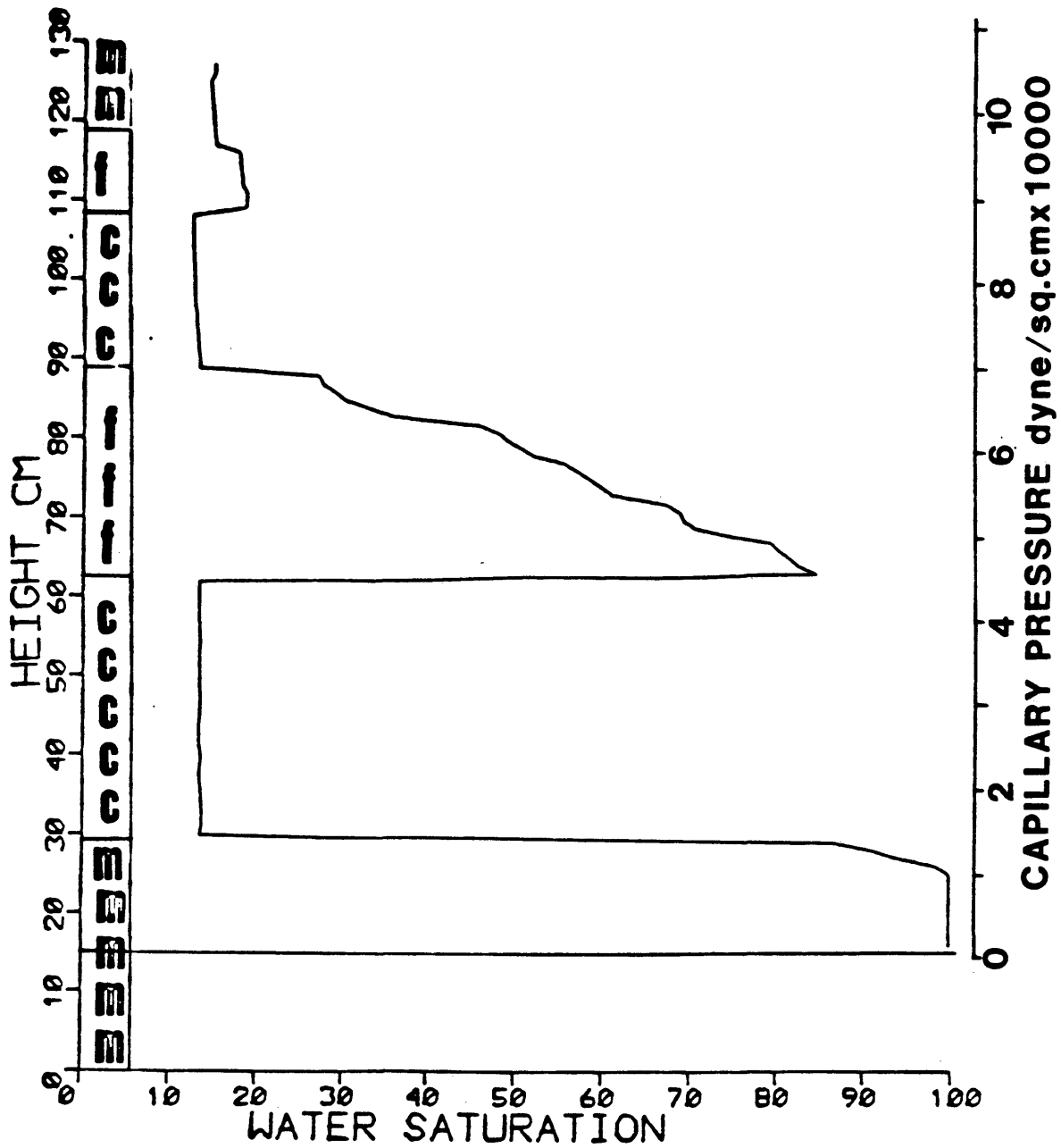


Figure 47. Layered sand column $n = 2.0$, one week later S_w vs. P_c .

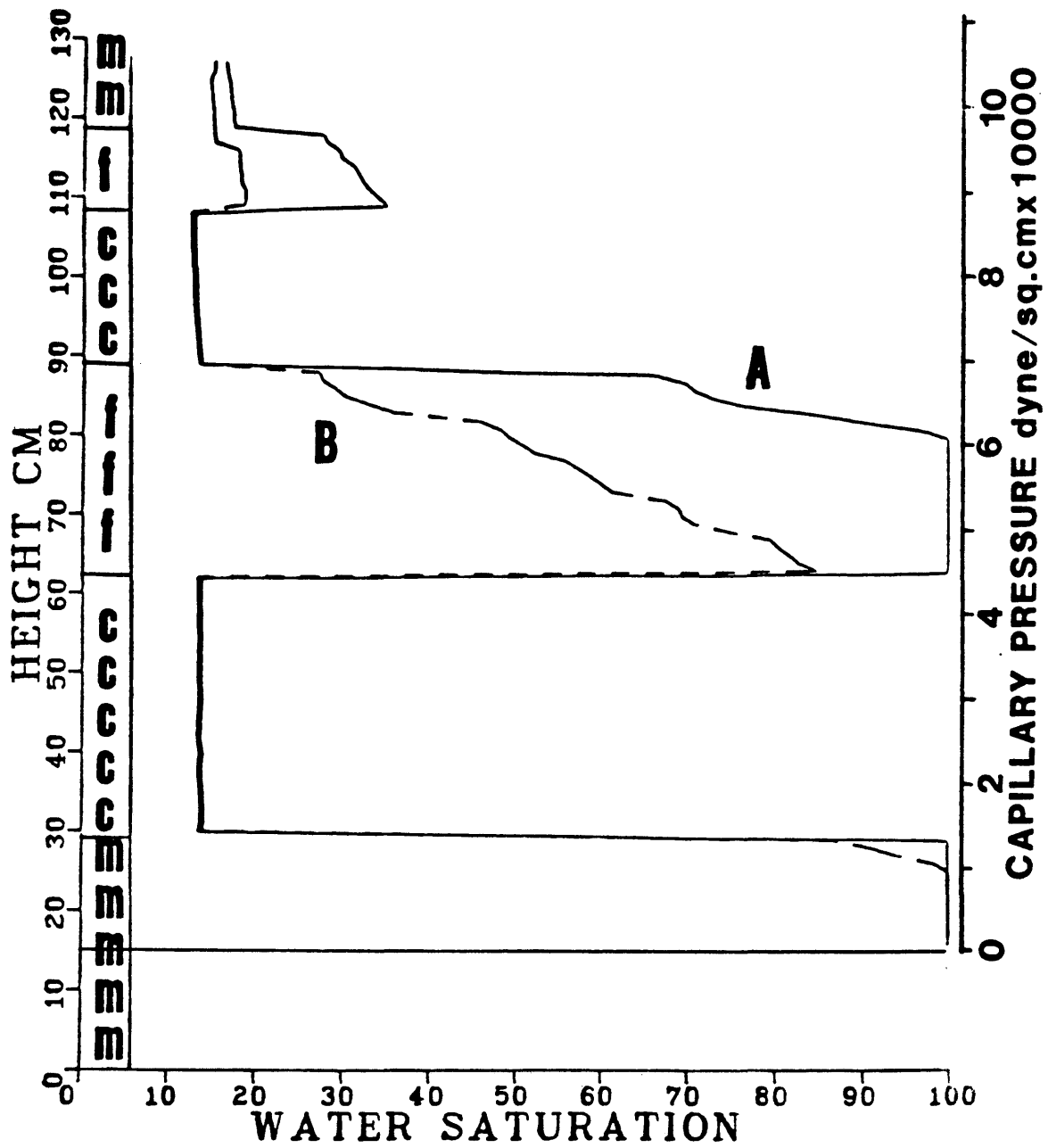


Figure 48. Layered sand column $n = 2.0$ - correlation of $S_w - P_c$ curves; A-one day later, B-one week later.

DISCUSSION OF RESULTS AND CONCLUSIONS

Porosities were very close but different. Porosities were calculated using several different methods, each of which was repeated many times. The method which gave the most consistent value was used. The porosity of the coarse sand was found to be 39%, it was found to be 38% for the medium sand and 36% for the fine sand. The matrix densities were calculated by using the porosity values. Densities were found to be 2.647 gr/ml for coarse sand, 2.66 gr/ml for medium sand and 2.652 gr/ml for fine sand.

Permeabilities found by the experimental set up were as follows: 251.8 mdarcy for coarse sand, 114.6 mdarcy for medium sand and 3.07 mdarcy for fine sand. These results were compared with the measurements made by a Ruska permeameter in the Petroleum Department of Colorado School of Mines. The results found by permeameter were as follows: 280 mdarcy for coarse sand, 118 mdarcy for medium sand and 3.5 mdarcy for fine sand. This comparison showed that the results of both methods were in agreement.

The resistivities of all three types of sand were very close when they were 100% brine saturated. R_0 was found to be 0.52 ohm-m for the coarse sand, 0.54 ohm-m for the medium sand and 0.58 ohm-m for the fine sand.

Cementation factor, m was calculated. It was found to be 1.392 for coarse sand, 1.395 for medium sand and 1.391 for the fine sand.

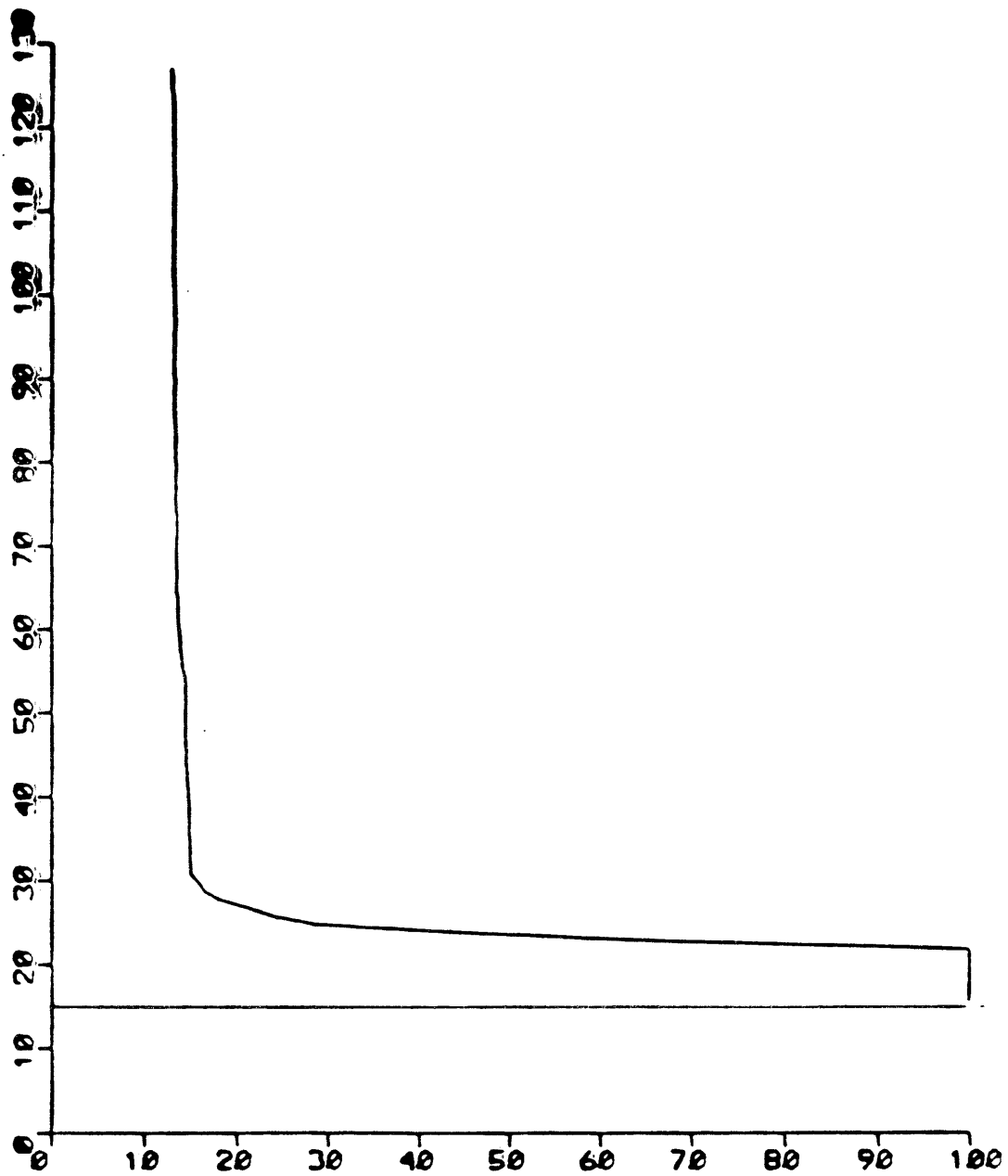
The saturation exponent, n , was calculated to be the same for all three types of sand. It was found that the grain size made no difference on the saturation exponent. It was found to be approximately 2.0 for all three sand types.

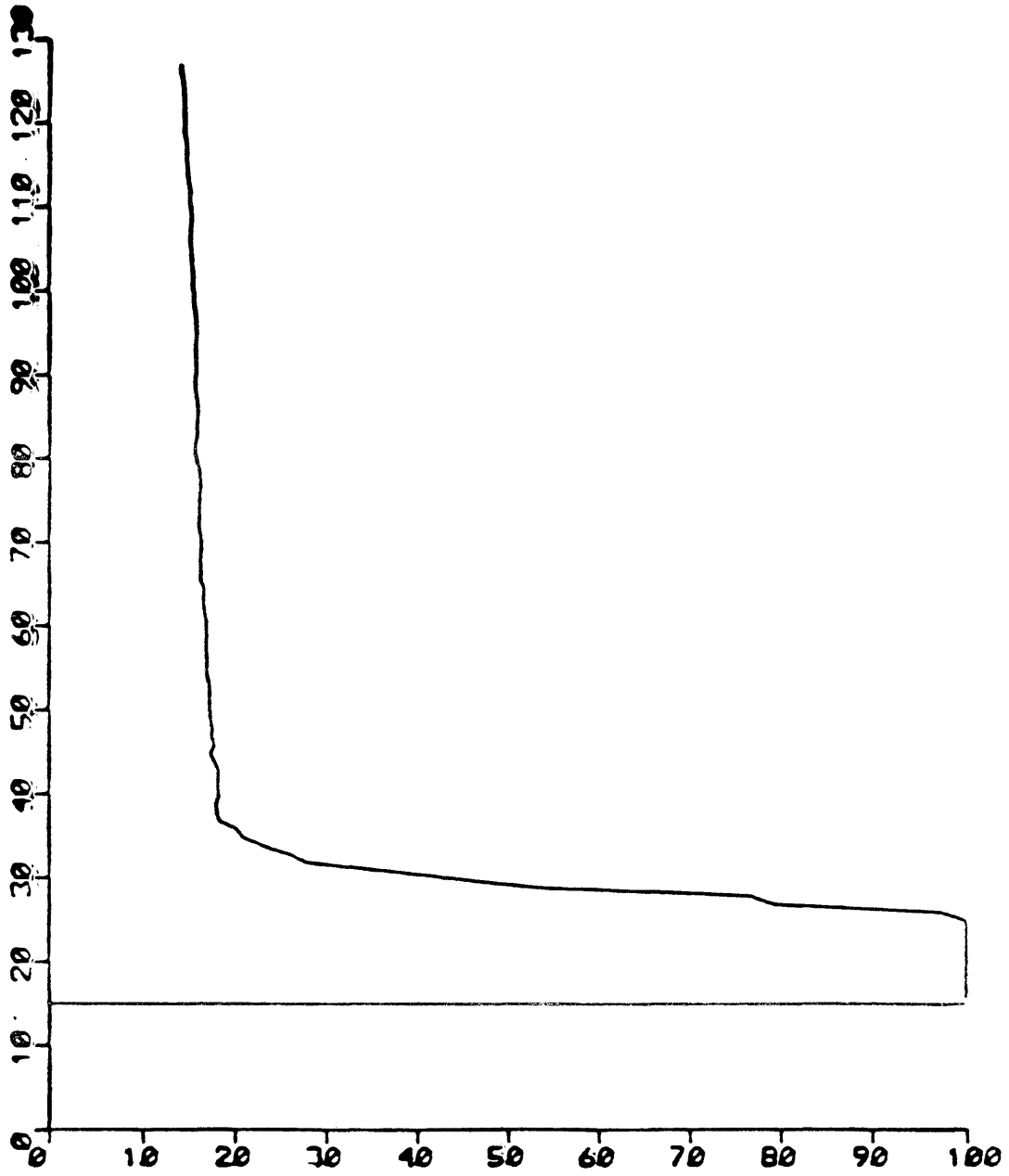
Through the resistivity measurements it was discovered that the coarse sand column reached its equilibrium in much less than 24 hours time, after which no changes were observed. For the coarse sand it was found that the irreducible water saturation was about 13%, and it was also found that only 7.5 cm of sand above the water table was 100% water saturated after one week. For medium sand it was different. Even though the column was slower to reach equilibrium, no changes were observed after 24 hours. The irreducible water saturation was found to be 15%. Also, the height of the 100% saturated sand above the water table after one week was found to be 16 cm. For fine sand column it took three days to reach capillary equilibrium. The irreducible water saturation was determined to be 18%. It was also

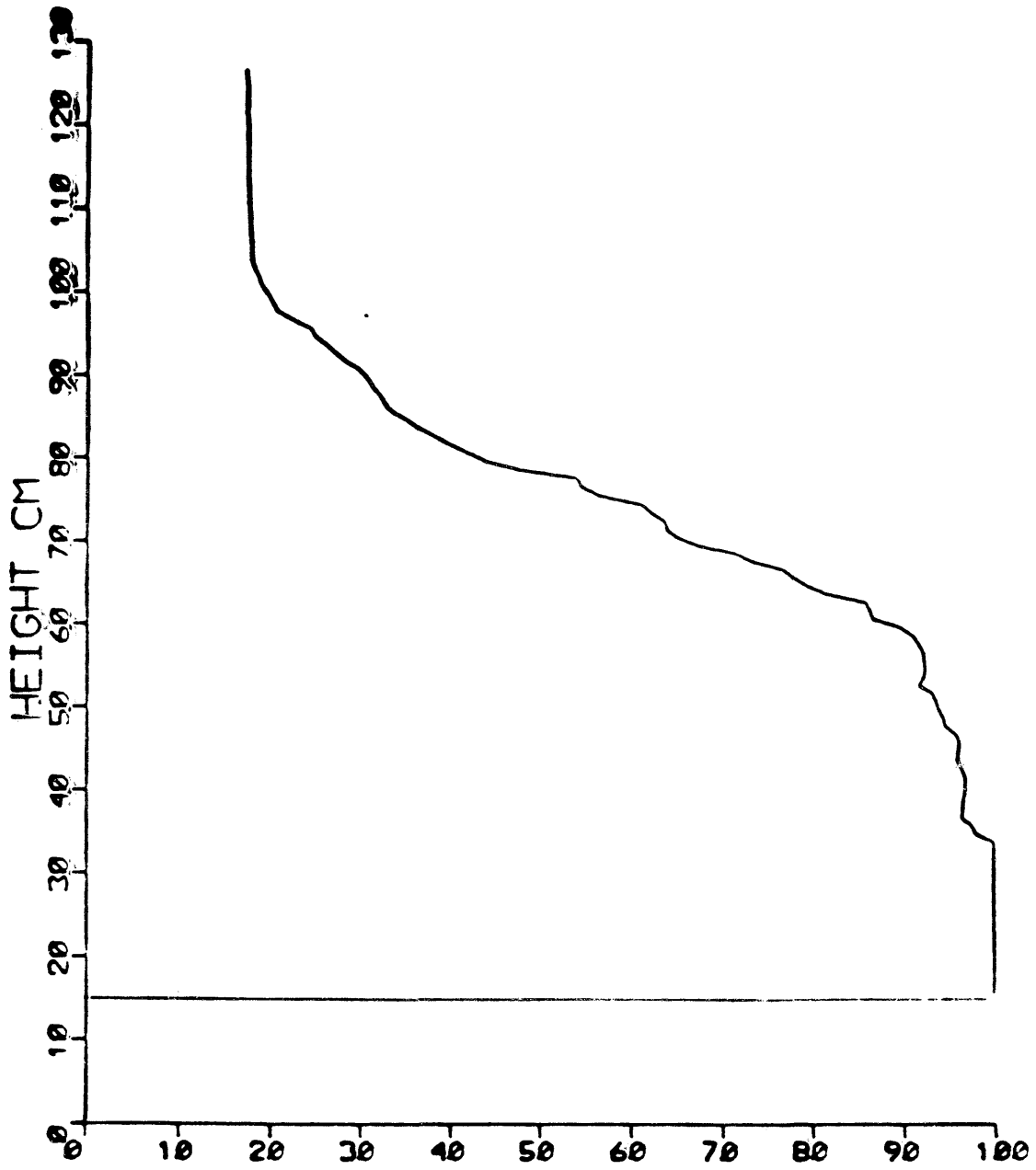
determined that the height of the 100% saturated sand above the water table was 35 cm. Another very important result was the transition of the S_w curve from the region of 100% water saturation to the region of the irreducible water saturation. This transition for the coarse sand was very sharp; it occurred over only 5 cm of the column. For the medium sand it occurred over 10 cm of the column. This transition was very different for the fine sand column; it occurred over 60 cm of the column.

It was observed that every type of sand behaved as if there was no other type of sand above or below it for the layered column. Comparing the results of a single type sand column with the layered sand column after one week made it clear that capillary pressure is mainly a function of height above the water table (see Figure 49).

In other words, it was found that the distribution of water saturation is a function of height above the water table. This shows that if the grain size distribution supplies such a capillary condition one can have 80% gas saturated sand right below 100% water saturated sand.







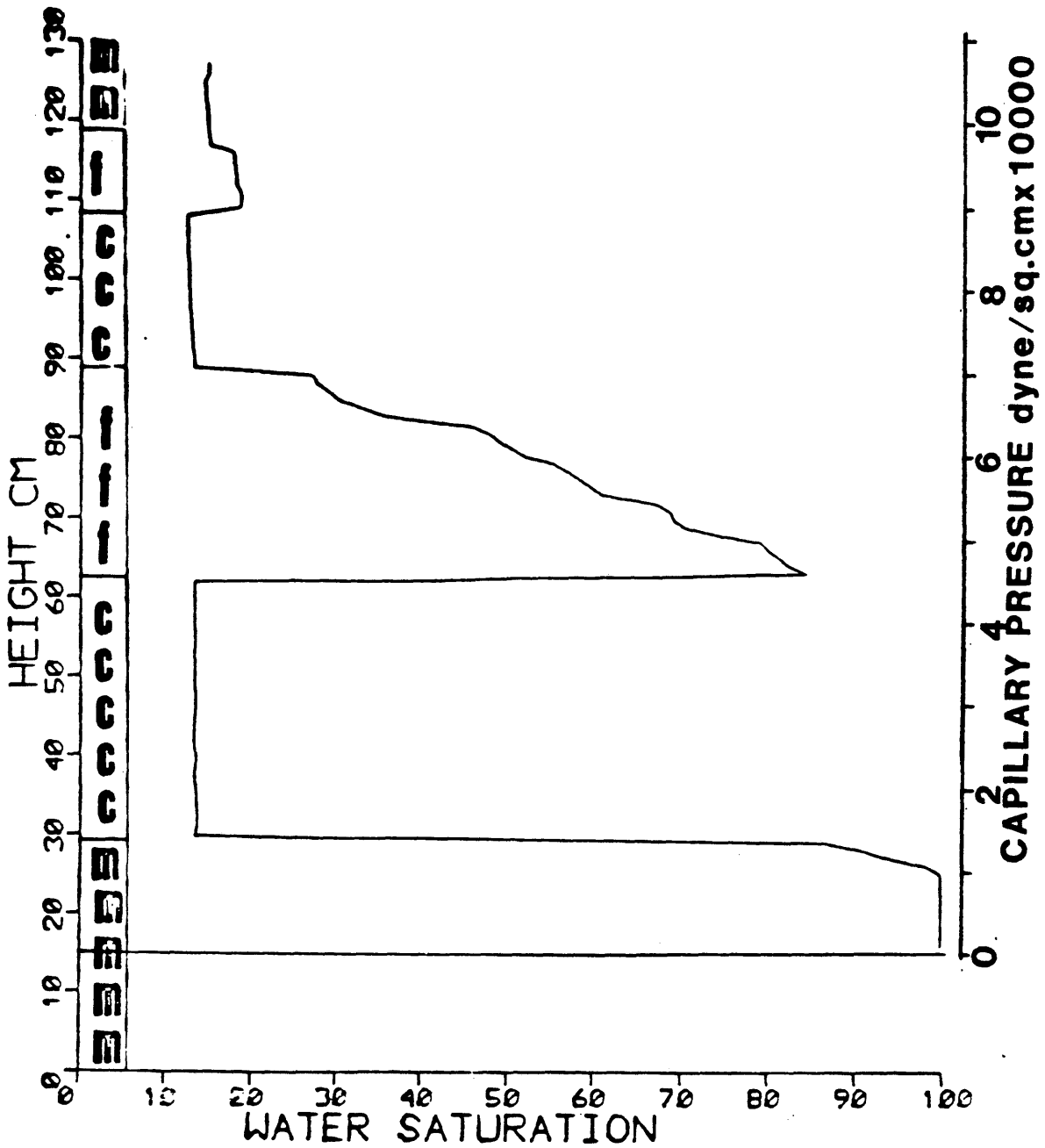


Figure 49. Correlation of S_w - P_c curve. Layered sand column with the S_w , P_c curves of coarse sand, medium sand, and fine sand column. Common delay is one week.

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