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A NEW EXPERIMENTAL METHOD FOR MEASURING
WATER CHARACTERISTIC CURVES OF SOILS

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# A NEW EXPERIMENTAL METHOD FOR MEASURING WATER CHARACTERISTIC CURVES OF SOILS

By

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## ABSTRACT

### A NEW EXPERIMENTAL METHOD FOR MEASURING WATER CHARACTERISTIC CURVES OF SOILS

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A new experimental method by which one can measure saturation as a function of capillary pressure in a soil sample was investigated. The method imposed a saturation on a sample and measured resulting capillary pressure. After each drainage increment a period of time was required for the sample to come to internal static equilibrium. In this paper, this was referred to as the "redistribution time". The effect of hydraulic gradient on both drainage time and redistribution time at different saturations was investigated.

The results showed that data obtained by this new method and the traditional method agree. Increasing the hydraulic gradient when high saturations exist speeded the drainage up but increased the redistribution time. At lower saturations a higher hydraulic gradient retarded both the drainage and redistribution processes.

Seven experiments determined the internal moisture profiles at the end of a drainage step which found not reproducible. It was postulated that the shape of such profiles depend on the internal microscopic structure of the sample.

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## LIST OF SYMBOLS

| | |
|---|---|
| $f$ | flux through a unit cross sectional area; [L/T] |
| $K$ | hydraulic conductivity; [L/T] |
| $H$ | hydraulic head; [L] |
| $L$ | distance from the origin in the direction of flow; [L] |
| $R$ | radius of curvature of the interface; [L] |
| $\sigma$ | interfacial tension; [F/L] |
| $P_c$ | capillary pressure across an interface; [$F/L^2$]. |
| $V$ | output voltage; [v] |
| $H_c$ | capillary pressure head; [cm of water] |

# CHAPTER 1

# INTRODUCTION

Water flow in soil is of great importance to engineering, hydrology and agriculture. The laws under which water flows in fully saturated soil have been studied extensively both experimentally and theoretically, however, flow in unsaturated zone needs more study.

In the unsaturated or vadose zone, soil water content depends on the difference in water and air pressure within the soil. In the vadose zone, water pressure is usually less than that of the air. The greater the soil water content, the smaller the difference between air and water pressures. The functional relationship, however, depends on the type of soil and is also subject to hysteresis. Curves depicting water content (or saturation) as a function of pressure difference (between soil air and water) are called "water characteristic curves". These curves can be obtained either through a drainage or wetting cycle. Starting with fully saturated soil (with water) and decreasing the soil water content successively completes a drainage (or drying) cycle. The wetting (or imbibition) cycle, on the other hand, requires

addition of water to initially dry soil. These curves are also called "water retention" or "capillary pressure vs. saturation" curves.

This thesis presents results of experiments which generate water characteristic curves for a given soil sample using a different method than those traditionally employed. The "pressure equilibrium" method, which has not been previously studied with this design and accompanying simple procedure, is reported and the results are compared to the traditional method of generating data.

The basic concept of this new method is to impose a known saturation on the soil sample and measure the resulting pressure difference under a static fluid (no flow) condition. The set up is designed to make the overall measurements faster. The use of a reluctant pressure transducer and associated electrical instruments makes the pressure difference measurements more reliable. A modified pressure cell technique is employed so that the size of the sample is relatively small and changing the sample saturation requires removal or addition of less wetting phase.

This thesis is divided into five chapters and an appendix. Chapters 2 and 3 present theory and experimental procedures used in this study, respectively. Comparison of results obtained from different equilibration techniques, as well as details of this new method, are presented in Chapter 4 of the thesis. The last chapter contains conclusions based

on the results and some recommendations for future work. The Appendix contains the procedure to calibrate the pressure transducer along with some data and also a list of apparatus components with names and addresses of parts providers.

# CHAPTER 2

# PROBLEM STATEMENT

## 2.1. General

Water characteristic curves have been generated by many investigators using a variety of different laboratory techniques. Topp, et al. (1967), have compared curves obtained by different methods and have shown that the results are dependent on the state of flow of the water. However, it is a common practice to use the water characteristic curves obtained under static condition of fluids in most cases.

This chapter presents a review of traditional methods for developing water characteristic curves along with a brief explanation of the new apparatus and approach employed in this study. This is followed by the objectives of this work. The theory and the physics of new system are described at the end.

## 2.2. Background

Richards published the first plots of water characteristic curves in 1928. These curves usually are determined on samples by changing the pressure difference across the air-water interface (the capillary pressure) in

increments and letting the water content adjust until equilibrium is achieved. The apparatus used to make such measurements is called a "pressure cell". The pressure cell was first described by W. Gardner et al. (1922).

The pressure cell method involves placing a soil sample in contact with a "pressure plate" or capillary barrier and controlling water and/or air pressures. The pressure plate is an essential component of a pressure cell. It is a porous plate made of glass, ceramic or a thin sheet of metal. In any case, the pressure plate has very small pores so that, when saturated, it allows only water and not air to pass through its pores over a range of capillary pressures chosen to study the saturation characteristics of the soil sample. The pressure difference at which air breaks through the plate is called the bubbling point or air entry pressure. Hence, any pressure difference less than the bubbling point applied across the plate is transmitted to the soil water in the cell. This feature of the pressure plate provides an efficient way to develop capillary pressures in the soil sample in the range of interest.

Capillary pressures are usually controlled by incrementally changing air pressure inside the cell on one side of the pressure plate and letting water pass through the plate and come to equilibrium with some known pressure on the other side of the plate. Once equilibrium is achieved, soil water pressure at any point inside the sample can be

determined, by knowing capillary pressure across the plate. If the sample height is small compared to pressure head differences applied across the plate, then a single capillary pressure can be assumed for the whole sample.

Depending on whether one is drying or wetting the sample, water will pass through the plate and either out of or into the sample. Once the air pressure inside the cell is increased by an increment, water will initially pass through the plate relatively fast because of the large hydraulic gradient across the plate. As water pressure across the plate approaches equilibrium, the gradient gets smaller and so does water flow through the plate. As a result, letting soil water come to equilibrium under a constant boundary pressure difference takes a long time, which may be on the order of days.

A variations of the pressure cell described above, was introduced by Su and Brooks (1980). In their procedure, the top of the pressure cell is open to the atmosphere. The method lets soil water drain out of the cell through the plate at the bottom and it can be added to the soil from the open top. As a result, the method enables investigator to get water characteristic curves during the wetting cycle and the drying cycle.

In their method a major improvement was achieved in that the method shortened the length of time required to generate a water characteristic curve. The basic idea of their procedure is to hold soil air at atmospheric pressure while,

in the drying cycle, a relatively high suction is applied to the soil water. Water is allowed to drain out of the soil into a burette that monitors the water content volumetrically. Once a desired volume of water is drained out, water suction is carefully reduced to stop the drainage and soil water suction is simply computed from the suction necessary to stop drainage. A slightly modified approach is employed to obtain wetting cycle data. In this procedure, capillary pressure and saturation on either drainage or wetting cycles is recorded when a pressure equilibrium is established. This is in contrast to the previously discussed procedures that wait for saturation to equilibrate with the applied pressures. By their method one can get data for the whole water characteristic relationship of a sample in a relatively short period of time.

One difficulty with the Su and Brooks method is that great care must be taken in adjusting water suction to stop drainage out of the cell. This is necessary because the occurrence of pressure equilibrium is established by the relatively tricky task of establishing a stable position of the meniscus in the outflow tube. Although they did not describe it as time dependent, the suction required to stabilize the meniscus would appear to be time dependent which could make the static equilibrium condition more difficult to identify. Failure to establish equilibrium would cause unwanted flow into or out of the cell which could change the status of the experiment from drainage to wetting or vice

versa at some points.

The pressure cell technique, in general, is the most commonly used experimental procedure to measure capillary pressure as a function of saturation. There are several other variations of the technique that have been used. Details of the variations, as well as other techniques, are described in the literature.

## 2.3. Objectives

The main purpose of this thesis is to investigate a new method for obtaining water characteristic curves for soil samples. The method includes a new experimental design and proper procedures. The basic principal of this method, as in Su and Brooks method, is recording data once pressure equilibrium in water is achieved rather than imposing a constant capillary pressure on the sample and waiting for the saturation equilibrium. The intent in the new method is to provide water characteristic curves faster than previous methods and not to take the risk of unwanted back-flow into the sample. The design is established to make measurements easier and at the same time more reliable than previous methods. This thesis will mainly investigate how well this new method could provide consistent and meaningful results and meet the mentioned expectations.

The second objective is to compare the data obtained by this method and the traditional method. This method is capable

of providing data based on both the traditional and the new method. Therefore, the investigator can make a quantitative comparison of results from the two methods. It is preferred for the comparison to be made on one packed soil sample.

This method applies more controls on the system compared to the traditional method. For example the drainage process is forced to occur in a desired manner by controlling the hydraulic gradient. On the other hand, the drainage is controlled and stopped externally when a desired volume of the wetting phase has drained out. As a result of above controls 1) a moisture profile forms within the soil sample at the end of a drainage period and, 2) if this internal moisture profile is not at static equilibrium condition, it will take some time for the moisture to redistribute and come to a static equilibrium condition. The drainage and redistribution processes are discussed in the next sections.

The third objective in this thesis is to study the resulting moisture profile within the soil sample at the end of a drainage period. It seems that the shape of such profile is critical with regard to the redistribution time. This study will address issues such as: a) How the moisture content varies along the height of a sample, b) What could the reason be for the formation of such profiles and, c) How far the profile is from being at a static equilibrium condition.

The last objective is to investigate how the controls in the new method can effect the drainage and redistribution

times. Results of this investigation could lead to an optimum criterion that minimizes the sum of drainage and redistribution time at each drainage increment. Note that the overall time to generate the entire water characteristics curve is sum of the drainage and redistribution times at several drainage increment. Therefore, any condition that reduces the drainage and redistribution time will contribute to shortening the time to generate water characteristic curve.

## 2.4. Theory

A fluid in porous media can be in thermal, chemical and/or mechanical equilibrium. The first two types of equilibrium are out of the scope of this work. Here the assumption is made that temperature gradients and chemical reactions do not exist in the fluid itself, nor between the fluid and its surroundings. Mechanical equilibrium is of interest in this study and occurs when there are no unbalanced driving forces on the fluid.

In the analysis of unsaturated flow problems, water characteristic curves can be developed under three different flow conditions: static (no flow), steady and unsteady flow. It has been shown that the flow condition has an influence on the relationship between capillary pressure and saturation, Topp et al (1967). Despite this fact, it has been common practice to use data based on a static equilibrium technique and apply it in the analysis of all unsaturated flow problems.

In static methods, capillary pressures and saturations are determined once the fluids are in a static condition i.e. when mechanical equilibrium is achieved. However, in order to measure capillary pressure at different saturations, flow of wetting phase into or out of the sample is inevitable.

It is an important fact that in the experiments to generate water characteristic curves under a condition of mechanical equilibrium the fluid particles should be at static equilibrium condition both externally and internally. The external static condition is established when the fluid particles in the system that are outside the soil sample and barrier are stagnant. Here after, for the purpose of this discussion, the soil sample and barrier will be described as a unit and referred to as the 'sample'. Note that in order to maintain the external static condition the net driving forces on each fluid particle outside the 'sample' should be zero. In this case there would not be any flow of fluids into or out of the 'sample'. As a result, a fixed saturation of the fluids would be held in the soil sample. The external static condition does not necessarily require the fluid particles inside the 'sample' to be static. They are free to move inside the soil matrix and at the upper face of the capillary barrier.

The internal static condition, on the other hand, is established when the fluid particles everywhere inside the 'sample' come to a static equilibrium condition. In this

situation the fluid particles would be at equilibrium with other fluid particles inside the matrix. Furthermore, it seems that once the internal static condition is achieved, the entire fluid system would be at true mechanical equilibrium.

The static fluid condition, for the purpose of this thesis, is the condition at which all fluid particles are in static mechanical equilibrium. Hence, there is no fluid motion anywhere in such a system.

Looking at unsaturated flow closely, we recognize that both the wetting and the non wetting fluids may flow. For example once a rigid, water saturated soil starts draining, as water drains out of soil, air enters. In other words, water will not initially drain out from a rigid soil matrix until air finds its way into the matrix to replace the drained water. Furthermore, in this work the assumption is made that the air density is negligible. Consequently, in unsaturated soil where the air exists as a continuous phase, it is assumed that air pressure is everywhere the same.

All experiments were run on disturbed sandy soil samples using air and Soltrol[1]. However, the same technique can be applied on any type of soil sample with any gas or liquid which is of interest. As mentioned before, the design and procedure are applicable to both wetting and drainage cycles.

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[1]A light hydrocarbon used as a wetting phase in most related research laboratories. It is more stable than water in regard to concerned chemical and physical characteristics.

## 2.5. Physics of the Problem

A review of the physical behavior of the system during two different periods is in order. The first period of interest is the drainage period. Drainage starts with the sample fully saturated. The air pressure is applied on top of the cell to initiate drainage. This occurs as the wetting phase is progressively replaced by air. The physics of the drainage process, which is basically the same in this study and the traditional method, is discussed below. The second period occurs in the new method when drainage from the 'sample' is forced to stop and covers the time required to establish an internal static condition.

Let us first introduce some basic concepts that are relevant to this analysis. Darcy's equation governs flow in the system. This equation in its simple form states that:

$$f = -K\frac{dH}{dL}$$

where f is the flux through a unit cross sectional area [L/T], K is the hydraulic conductivity [L/T], H is the hydraulic head [L], and L is the distance from the origin in the direction of flow [L]. The term dH/dL is the hydraulic gradient. In a saturated system the conductivity K is constant, whereas, in unsaturated media it is a function of the capillary pressure. In this section we will make use of Darcy's equation qualitatively.

Another basic relevant equation is Laplace's equation of

capillarity. This equation relates capillary pressure across an interface to the radius of curvature of the interface.

$$R=\frac{2\sigma}{P_c}$$

where R is the radius of curvature of the interface [L], $\sigma$ is the interfacial tension [F/L], and $P_c$ is the capillary pressure across the interface [$F/L^2$].

In an unsaturated porous media the radius of curvature of the interface is an indication of saturation. The smaller the radius, the less the saturation. For a given fluid pair the interfacial tension $\sigma$ is constant. Then Laplace's equation requires that the capillary pressure remain constant in order for the saturation to remain constant. Increase in the capillary pressure, for instance, implies that the interface has moved towards the corner in a pore space. It results in a smaller radius of curvature and less saturation when the fluids return to a static situation. Obviously the interface adjustment, which is related to the saturation change, may take some time to occur since it requires addition or removal of some of the wetting phase to the pore space.

In the pressure cell study, the experiment starts when the sample is fully saturated. Then the air pressure on top of the cell is increased and held constant at a high pressure. The interface, which is originally horizontal, is not capable

of holding any capillary pressure. As a result, the pressure in the air is totally transmitted to the wetting phase across the interface. At the same time, the wetting phase pressure on the other side of the cell is almost constant and smaller than that of air. This situation produces an hydraulic gradient in the wetting phase that, according to Darcy's law, drains the wetting phase from the sample. The hydraulic gradient, and therefore the drainage flux, depend on the capillary pressure across the cell. For instance, given a conductivity and a wetting phase pressure at the bottom of the cell, the greater the air pressure the higher the drainage flux out of the sample.

As the drainage proceeds, air will break through the soil matrix. It will exist as a continuous phase throughout the sample. Consequently, an interface with some curvature will be formed in the pore spaces. At the bottom boundary of the sample, on top of the pressure plate, an important development will occur. The air pressure is too small to force air through the plate. So an interface will form at the top surface of the plate that represents the applied capillary pressure according to Laplace's equation. This interface can be expected to develop its full curvature more quickly than the interface inside the matrix because: 1) it requires much less wetting phase desaturation due to its smaller pores compared to pores that are internally desaturating in the soil, 2) the distance that the wetting phase fluid particles must move in order to

let the interface curvature develop in the plate is shorter compared to that in the soil, and 3) the conductivity of the path along which the particles move is usually greater in the plate since it remains fully saturated whereas the soil sample does not. At this point, the difference in radii of curvatures on top of the plate and inside the soil matrix will results in a pressure difference within the wetting phase between the two locations. This pressure difference could produce a hydraulic gradient that according to Darcy's law is the reason for the drainage out of the soil sample.

While the drainage is proceeding, the interface inside the soil matrix will retreat and move towards the corner of the pore spaces. It is only by this retreatment that some volume of the wetting phase could be removed from a rigid pore space. The interface at its new position has a smaller radius of curvature and is bearing a greater portion of the applied force so that a greater capillary pressure exists as described by Laplace's equation. As a result of such retreatment, the wetting phase pressure adjacent to the interface will decrease. This pressure drop will, in turn, decrease the hydraulic gradient in the wetting phase across the plate, assuming that the wetting phase pressure at the bottom of the cell remains constant. In addition, the wetting phase conductivity K of the soil decreases logarithmically as the drainage proceeds. Decreases in the hydraulic gradient and conductivity throughout the soil sample result in a decaying

type drainage flux over time according to Darcy's equation.

This decaying behavior of the drainage flux over time makes the drainage process "lengthy". It is the main difficulty with the traditional method of generating water characteristic curves. The method requires the gradient and the drainage to decay to practically zero. Therefore, it will take a relatively long time, especially at low saturations.

Two controls are employed in this study to deal with the length of the drainage time. First, the air pressure on top of the cell is controlled to make the drainage faster. As discussed before, higher air pressure causes a higher hydraulic gradient in the wetting phase. This could be used to increase the initial drainage flux out of the sample according to Darcy's equation. However, as the drainage proceeds this does not prevent the hydraulic gradient or the conductivity from dropping.

Secondly, once a desired volume of the wetting phase is drained out, and before the hydraulic gradient decays significantly, the drainage is stopped externally. In other words, the drainage increment is controlled as a variable. By employing both of the above controls, the new method could make the drainage occur faster compared to the traditional procedure.

The second period in physical behavior of the system is referred to as the "redistribution" period. Su and Brooks (1980) have referred to a somewhat similar behavior as the

"pressure equilibrium" period. Despite the fact that their procedure is different from the procedure employed in this study, the physical responses of the two systems are similar. This period is discussed here from both points of views.

In the new method the redistribution period starts when drainage is stopped. At this moment the external static condition is, for all practical purposes, achieved and a fixed saturation is imposed on the 'sample'. As discussed earlier, right before stopping the drainage the interface on top of the plate is almost fully developed and the wetting phase pressure in the plate is close to zero. When the drainage is stopped externally, flow of the wetting phase from the soil into the plate will still occur due to the existing hydraulic gradient. Therefore the interface in the soil and on top of the plate will retreat accordingly. This retreatment will decrease the overall pressure of the wetting phase in the soil and increase that in the plate. This internal flow will go on until the wetting phase pressure in the soil and in the plate are equilibrated. Then the flow will stop and the internal static condition will be established.

The redistribution period could also be analyzed from a different point of view. Consider the moisture profile within the soil sample at the beginning and at the end of this period. Noting that the wetting phase has been flowing out of the sample right before stopping the drainage, one may conclude that the moisture profile at the beginning of this

period would not be at a static equilibrium condition. On the other hand, by definition, at the end of the period the moisture profile within the sample must be at static equilibrium condition. From this point of view, the second period represents the redistribution of moisture inside the 'sample'. For the final equilibrium to be established, this internal redistribution is accompanied by a small amount of moisture flowing from the soil into the plate. Note that despite a known overall saturation of the 'sample', a single capillary pressure can not be assigned to the sample during this period. The reason is again the dynamics of the internal moisture redistribution, as described earlier.

In order to obtain the approximate shape of the moisture profile within the sample at the end of a drainage step, a set of supplementary experiments was conducted. It was assumed that the hydraulic gradient and drainage increment have an effect on the shape of such profiles. Therefore, a relatively high pressure gradient was applied to the wetting phase to drop the sample saturation from 100 to 50 percent in one step. The intent was to create a nonuniform moisture profile that could not redistribute to a static equilibrium condition before the moisture distribution could be measured. The moisture distribution was measured by removing soil samples from different regions of the sample and oven drying them.

Several additional experiments were conducted to investigate the effect of the two controls employed in this

new method on the drainage and redistribution times. Based on a simple analysis, it seemed likely that the hydraulic gradient has the predominant role both theoretically and practically compared to the drainage increment. Therefore, the drainage and redistribution times were measured under two different hydraulic gradients for equal drainage increments.

# CHAPTER 3

# EQUIPMENT AND PROCEDURE

## 3.1. General

This chapter contains a description of each component of the apparatus, including the pressure cell, burette, valves and pressure transducer with its required accessories (Figure 1). The last section describes the experimental design, set up and procedure.

## 3.2. Pressure Cell

The pressure cell used, like those previously described, is a small cell composed of an inner cylinder, outer cylinder and two end caps (Figure 2).

The cell had an inside diameter of 5.6 cm and an effective internal height of 3.2 cm. It was designed short so that saturation remained fairly constant over the height of the sample. The short cell also allowed for easy soil packing and minimized drainage time.

To minimize diffusion of liquid through the body of the cell, it was made of aluminum. A round ceramic plate with epoxy paint sealing the edge was used as a capillary barrier

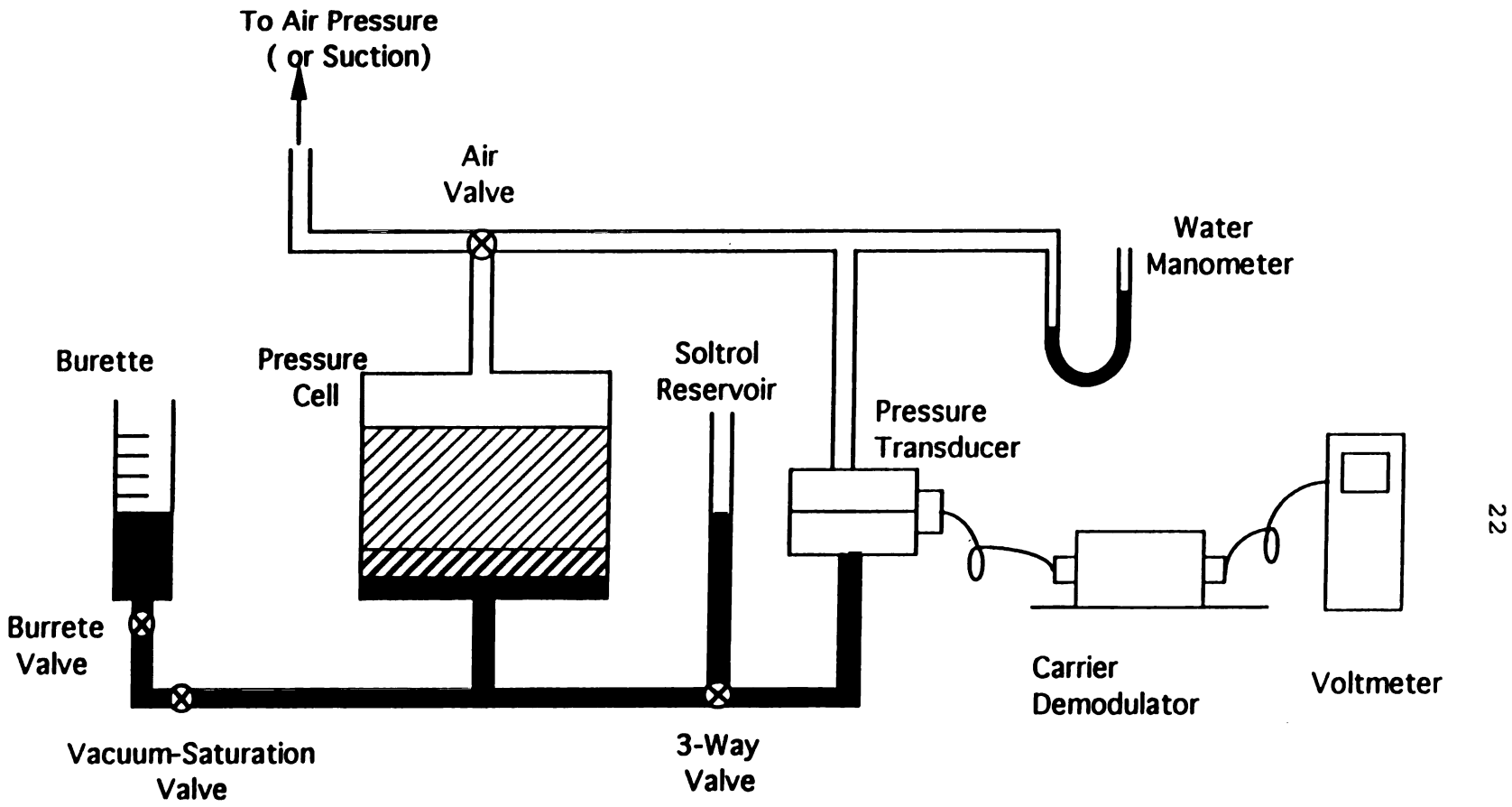



Figure 1 Schematic of Experimental Apparatus

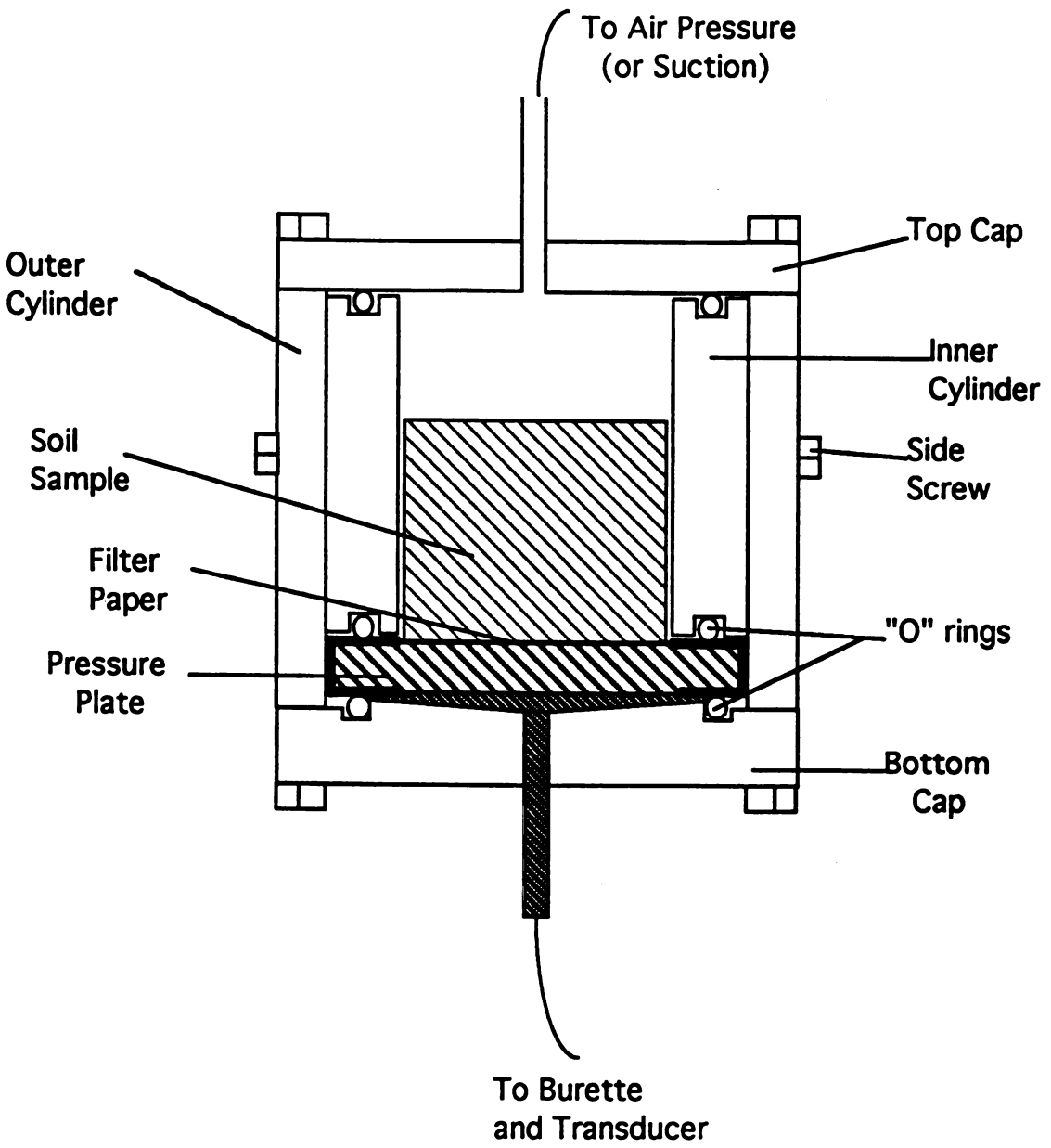



Figure 2.
Pressure Cell Schematic

to transmit suction to the soil water. Two O-rings on the top and bottom of the pressure plate along with the epoxy provided a seal, while on the top of the cell a single O-ring was used. A paper filter placed on the top of plate prevented clay-sized particles from entering the plate. Side screws were provided to fix the inner cylinder relative to the outer one in order to permit the bottom seal to be achieved before packing soil into the cell.

### 3.3. Burette

A glass, 25 ml burette with a bottom stop cock and 0.1 ml graduations was used during the experiment. The stop cock was a high quality, zero-displacement valve. It was used to stop and start the drainage in order to impose known saturations on the sample. Thick-walled Teflon tubing was used to connect the burette to the cell and transducer, Figure 1. The liquid content of the sample was monitored volumetrically using this burette.

### 3.4. Pressure Transducer

The most critical device used in the experiment was the pressure transducer and its associated components. A very sensitive variable reluctance pressure transducer was used (model number CJVR, C.J.Enterprises, Tarzana, CA). It was designed to measure low and medium gage, as well as, differential pressures. Using a carrier demodulator and

voltmeter, the transducer produced a 0 to ±10 volt DC output in response to a 0 to maximum pressure difference on its diaphragm.

A brief technical description of the transducer from the manufacturer's manual states:

> "The transducer consists of basically a flat pressure sensing diaphragm (field replaceable) clamped between two matched case halves each containing electrical pick off coils. Applied pressure deflects the diaphragm which is detected by the two pick off coils. When the coils are connected as two opposing legs of a bridge circuit, the resultant bridge output is proportional to pressure. Bleed screws are provided in both case halves to facilitate complete liquid filling for dynamic measurements."

The pressure transducer was connected across the ends of the cell. One port was always filled with Soltrol, whereas, the other port was connected to the air source as shown in Figure 2. This pressure measurement reflects the pressure difference between air and Soltrol i.e. the capillary pressure, $P_c$ , across the plate.

A calibration curve was frequently developed to convert output voltage into pressure difference. Characteristics of the transducer and other related electrical devices were investigated and shown to be satisfactorily stable. A typical result is discussed in the Appendix.

### 3.5. Valves

Besides the burette valve, which was previously

described, three other valves were used in the system (Figure 1). They are referred to as the 3-way valve, air valve and vacuum saturation valve. The vacuum saturation valve was used for initially saturating the plate and the soil. It had two important characteristics. First, it was capable of providing adequate seal when a relatively high vacuum (around 700 millibar) was imposed on the air phase at the top of the cell to take the air out. Secondly, it was a displacing valve (not a desired characteristic) that was capable of a fairly fine regulation of valve opening and therefore liquid flow. With this valve, the Soltrol inflow to the cell to initially saturate the sample was kept to a reasonably low rate. This was judged necessary as a relatively high inflow rate could have changed the internal structure of the packed sample, especially at the unrestrained top surface of the soil. The internal volume of this valve was measured and accounted for during the experiment. Once the sample was saturated, the vacuum was released and this valve was left open for the rest of the experiment.

The air valve was a three-way stopcock. It had a rotating core with T-shape opening. It connected all three air lines during the experiment. In order to initially vacuum saturate the sample, this valve was set so that the suction was transmitted only to the cell. During the calibration, however, the air pressure was applied only on the transducer through this valve.

The 3-way valve on the liquid side was a 3-way ball valve with directional flow switching. It had an inlet port that could be connected to either of the other two ports. The inlet port was connected to the transducer. During the experiment this valve was positioned so that the transducer was connected to the pressure cell. For calibration purposes and during the initial vacuum saturation of the sample, the valve was used to isolate the cell and connect the transducer to the constant pressure head Soltrol reservoir. The calibration setup and procedure are discussed in the next section.

### 3.6. Set up and Procedure

#### 3.6.1. Set up

The procedure used here, as discussed before, is a variation of traditional pressure cell technique. The main differences are:

1. A desired saturation is imposed on the sample and the resultant capillary pressure is measured, as opposed to the traditional method that leaves the soil under a constant capillary pressure to come to saturation equilibrium over time.
2. A pressure transducer along with a carrier demodulator and voltmeter are used to monitor the capillary pressure. The setup allows a quick, reliable measurement.
3. An aluminum cell is used to minimize the effect of

diffusion through the cell body.

These differences enable the investigator to obtain the whole water characteristic curve in a more convenient manner than with other static devices and procedures. The design allowed data to be obtained both by this new method and the traditional method. Figure 1 shows the setup schematically.

The transducer was wired to the carrier demodulator and a voltmeter. It had a sensitive replaceable diaphragm and because of the type of soil sample a 0-1 psi diaphragm was employed. The demodulator was set so that the output signal had the maximum possible value when the transducer was subjected to the maximum pressure difference. By setting the controls on the demodulator, a 0-10 volt output was registered on the voltmeter when the transducer was subjected to its full range of pressure differences. By locating the transducer at the same elevation as the midpoint of the sample, it directly provided capillary pressure corresponding to the mid sample position whenever the fluids were static.

### 3.6.2. New Method Procedure for Determination of $P_c(S)$

The general procedure was to remove a specified volume of water from the soil and measure the resulting capillary pressure. The drained volume was determined with the graduated burette and the saturation was calculated. The capillary pressure was measured with the pressure transducer which was connected to a voltmeter. The voltage signal was registered on

the voltmeter and was converted to capillary pressure by using the calibration data.

Vacuum saturating the space beneath the plate and the plate itself was the first step. The vacuum saturation valve was closed and the burette valve opened. An oven dried pressure plate was employed and the vacuum was created by applying 700 millibar air suction on top of the plate. Then the vacuum saturation valve was opened to let Soltrol saturate the space and the plate. When the saturation process was complete the air suction was removed.

Any air trapped inside the space was identified and removed by turning the cell over and applying a small suction on top of the burette. Then the burette valve was closed. A paper filter was placed on top of the pressure plate and the system was weighted.

A fine sandy air-dried soil was packed on the filter paper and plate; the soil had a free top surface. The packing device was a 20 cm long, 3 cm diameter tube with a 2 mm mesh screen at the bottom to help uniformly distribute the soil particles. The tube was placed on the plate, filled with the soil, pulled up slowly and rotated uniformly until the cell was almost filled up. The cell was dropped 10 times from an elevation of 3 cm. Then the free top of the soil was hammered by dropping a 1.5 kg weight 10 times from a 1 cm elevation. When the packing was complete, the system was weighted again and vacuum saturated, in place, within the cell.

Vacuum saturating the soil was almost the same as vacuum saturating the plate. As rationalized earlier, the vacuum saturation valve was used to insure a small flow rate of Soltrol during saturation. First the sample was over saturated. Then the high vacuum was removed and the vacuum saturation valve was totally opened. The system was left under a small hydraulic gradient for a long time so that excess Soltrol would drain out. The volume of Soltrol necessary to fully saturate the sample was monitored with the burette. It was corrected for the small volume added to the system by totally opening the displacement valve (vacuum saturation valve) and was considered to be the total pore volume. At the end, the pressure transducer along with the Soltrol reservoir and other electrical devices were connected to the system as shown in Figure 1.

Before starting the experiment, the transducer was calibrated. It was also frequently calibrated in place during the experiment. Calibration was achieved by positioning the air valve and the 3-way valve in Figure 1 such that the pressure cell and burette were isolated from the transducer. Transducer calibration was accomplished by controlling the regulated air pressure on one side of the transducer and connecting a static Soltrol reservoir to the other side. Data for calibration were obtained by progressively increasing the air pressure on the transducer and decreasing it back to zero. Air pressure was monitored with a U-tube water manometer. The

accuracy of the calibration procedure is discussed in the Appendix.

The drainage branch of a water characteristic curve was initiated by positioning the air valve so that air pressure was applied to both the transducer and the cell. The 3-way valve was set to connect the transducer to the cell and isolate the Soltrol reservoir. With the burette valve closed, relatively high air pressure was applied to the top of the cell. Soltrol was then allowed to drain out of the sample into the burette under a relatively high pressure gradient by opening the burette valve. When the desired volume of Soltrol was drained into the burette, the burette valve was closed again. Saturation of the sample at that point was calculated from the known Soltrol drainage and the initial Soltrol volume in the pore space. Output voltage was read on the voltmeter and converted to capillary pressure by using the calibration curve.

The process of desaturating the sample and measuring capillary pressure and saturation went on by opening and closing the burette valve and reading the voltmeter and burette. Smaller drainage increments were employed where the water characteristic curve exhibited large values of $dS/dP_c$.

Once a specified volume of Soltrol was drained out of the sample, a period of waiting was required for the system to equilibrate (redistribution period) before additional Soltrol was drained. During this time Soltrol was not allowed to drain

out, but the voltage signal on the voltmeter was observed to drop to some stable value asymptotically. As rationalized earlier, this transient time was attributed to the redistribution of the moisture inside the sample. In this study, the time required for voltmeter stabilization is referred to as "redistribution time".

During redistribution, the voltage was recorded periodically until it approached a stable value. However, the length of time required to achieve internal equilibrium was not well defined because it is approached asymptotically. Furthermore this time was observed to depend upon saturation. Therefore, the actual time recorded as necessary to achieve redistribution was dependent on the operator's judgement. In this study the voltage was recorded for a long time after each drainage step to insure that most of the change in capillary pressure had occurred. Despite the subjectivity associated with the determination, a consistent criteria was used throughout the experiments.

### 3.6.3. Traditional Method Procedure for Determination of $P_c(S)$

The second objective of this study was to compare the results obtained by this new method and the traditional method quantitatively. To achieve that, in between the new method points and within the same run, some data were collected by allowing the sample Soltrol saturation to equilibrate under an

applied pressure difference. The procedure was as follows:

The drainage curve was developed by increasing air pressure to its maximum value in four steps. Within each step, data were obtained using the previously described procedure. At the end of each step the burette valve was left open for a relatively long time so that the soil sample could drain to equilibrium under the imposed pressure difference. Then a single data point was recorded that was based on the traditional method. An indication of the occurrence of true equilibrium was obtained by shutting the burette valve off and determining that no significant change on the voltmeter could be observed. This would occur if no outflow had been occurring when the valve was closed which indicated, by definition, that equilibrium existed. By this technique, data were obtained using both the traditional method and the new method on a drainage cycle.

At the end of each experiment the Soltrol mass balance was checked by oven drying the sample. In addition, the transducer was recalibrated. Comparison of before and after calibration curves show sufficient consistency in basic characteristics of the electrical devices used in the experiment. The Appendix includes a set of such curves.

Although only drainage cycle curves were generated in this study wetting cycle curves could have been measured. These would be initiated after the Soltrol was brought to residual saturation on the drainage cycle.

### 3.6.4. Procedure for Determining Moisture Profiles Within the Soil Samples

To achieve the third objective seven experiments were conducted to measure the moisture profile within the sample at the end of a drainage step. The air valve and 3-way valve were positioned to isolate the transducer and the Soltrol reservoir since no measurement of the capillary pressure was needed in these experiments. The soil was packed and vacuum saturated in the same way as explained earlier. The soil sample was brought to a fully saturated condition while the saturation was monitored by the burette. At this time the burette and vacuum saturation valves were fully open.

Desaturation of the sample was initiated by applying 70 mbar air pressure to the top of the cell. As a result, Soltrol was driven out of the soil under a relatively high hydraulic gradient. When the Soltrol saturation was reduced to approximately 0.5, the burette valve was closed and the air pressure reduced to atmospheric. The soil sample was stratified into three layers. Each layer was divided into three smaller samples. The samples were weighted, oven dried and weighted again. The Soltrol saturation of each sample was computed and a coarse moisture profile developed. In addition, the total saturation was checked by the mass balance.

The stratifying process was conducted as quickly as experimentally possible to minimize internal moisture redistribution during this process. On average, 95% of the

mass of soil samples was collected and oven dried for saturation determination during the stratifying process.

### 3.6.5. Procedure for Determining the Influence of Hydraulic Gradient

The final set of experiments measured the drainage and redistribution times at different saturations under two different hydraulic gradients. These experiments were performed using the new method procedure except that the air pressure was periodically adjusted in order to maintain a constant hydraulic gradient. Two soil samples were packed and vacuum saturated as explained earlier. The transducer was connected to the system and calibrated before running the experiment.

With the burette valve closed, the air pressure was applied on top of the first sample so that the voltmeter registered 2 volts. By opening the burette valve, Soltrol was allowed to drain out of the sample into the burette. During the drainage increment, the air pressure was adjusted so that the voltmeter remained stable at 2 volts. The time required to drain the required volume of Soltrol was monitored with a stopwatch. At the end of the drainage step, the redistribution time was determined. The experiment continued by progressively desaturating the sample until the times required became too large. The second sample was subjected to a 4 volts gradient during the drainage. Except for this, it was desaturated in

the same way as the first sample. The drainage increments were the same in both cases.

# CHAPTER 4

# RESULTS AND DISCUSSION

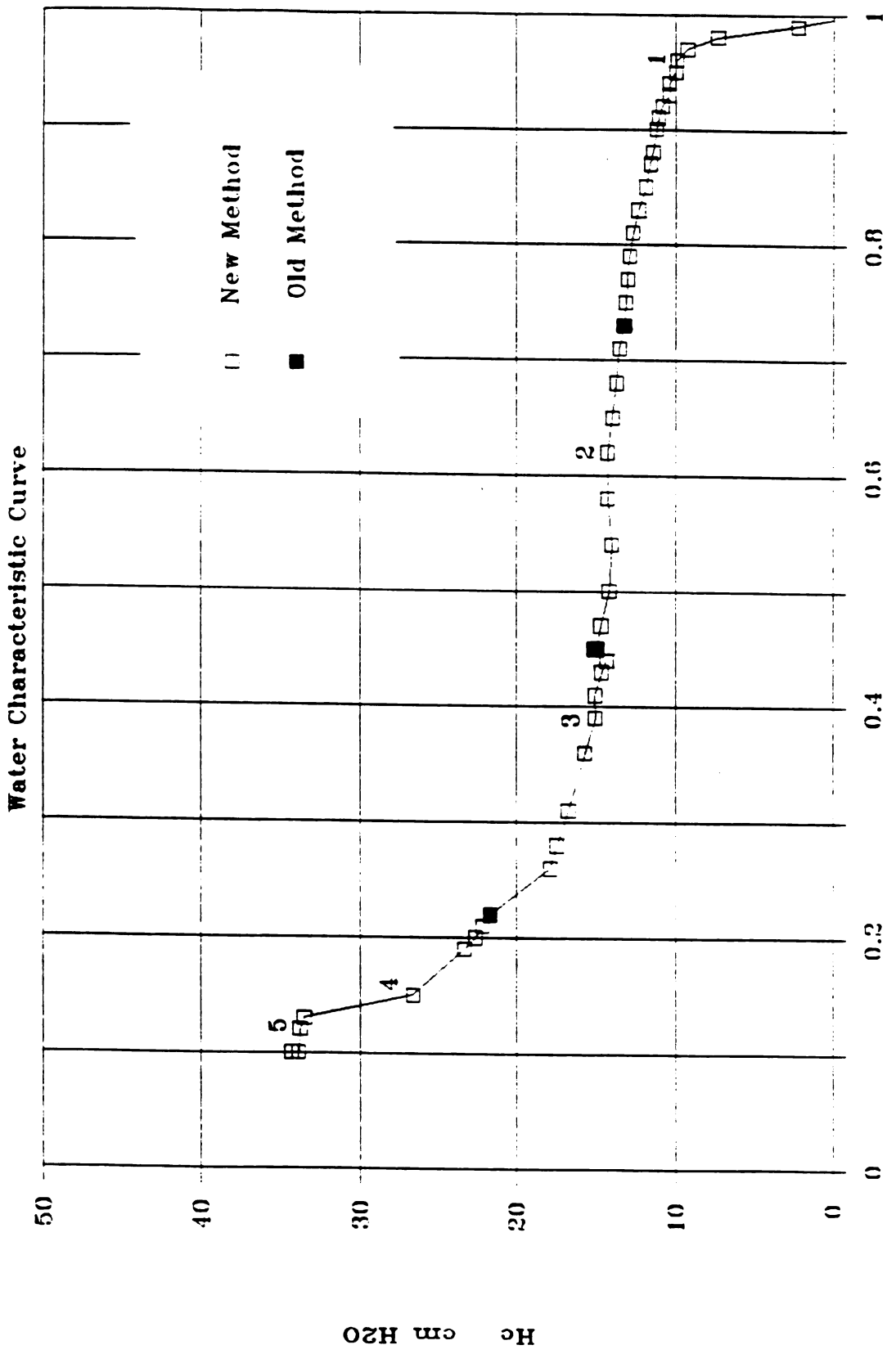
## 4.1. General

An example of a water characteristic curve on a drainage cycle obtained by the procedure previously described is presented in this chapter. The results of the supplementary experiments and the drainage time measurements are presented next. The last section includes a general discussion on the redistribution process in the new method and the results of the redistribution time measurements.

## 4.2. Water Characteristic Curves

A typical water characteristic curve obtained by the described procedures is shown on Figure 3. Solid squares represent data from the traditional method, where open squares are data recorded by the new method. The wetting phase saturation of the sample is shown on the horizontal axis and the capillary head in centimeters of water is on the vertical axis. The data were obtained on a single drainage cycle experiment on one packed sample. Soltrol was used as the wetting phase and air as the non wetting phase.

Figure 3

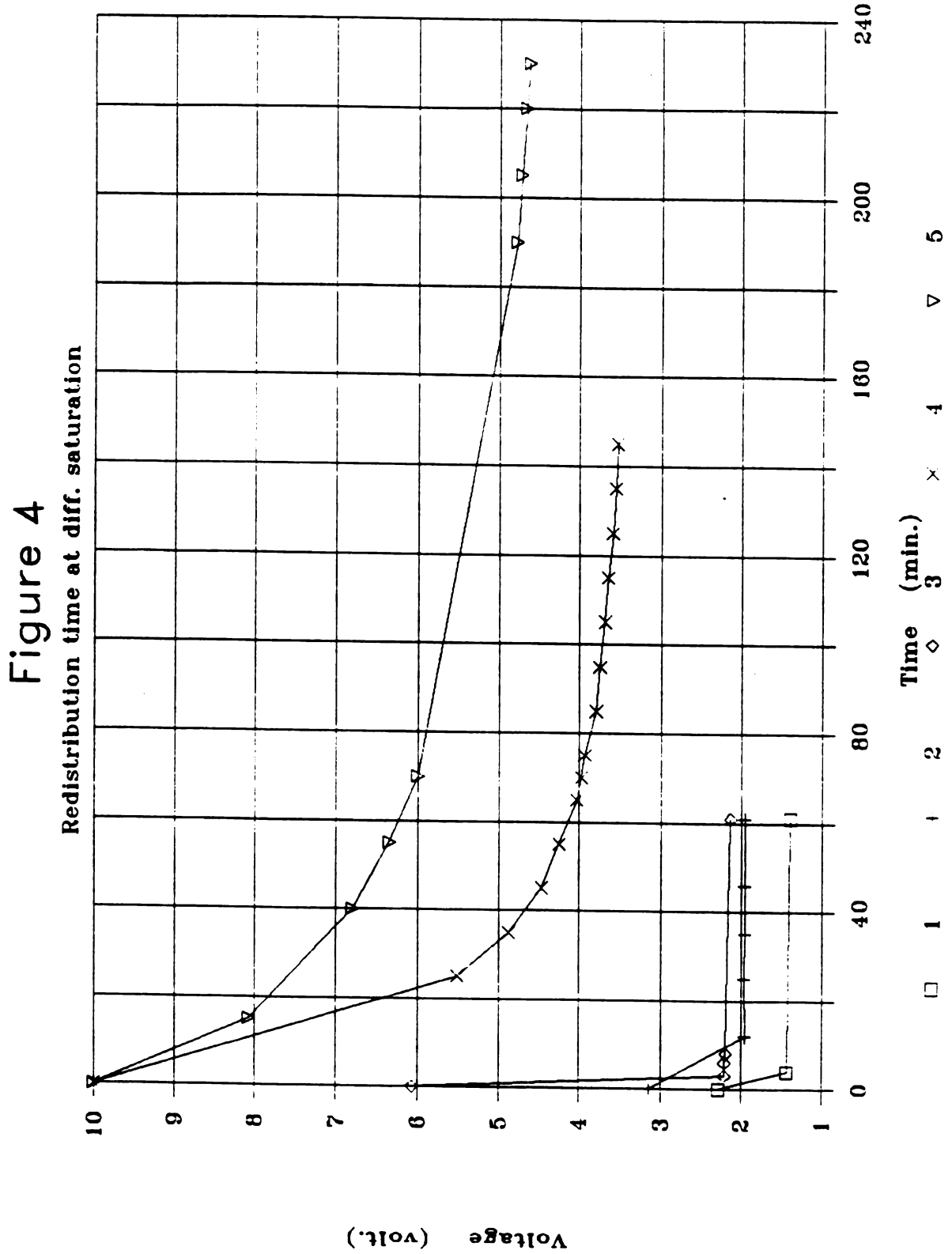

Water Characteristic Curve
New Method
Old Method
Hc cm H2O
Sat.
50
40
30
20
10
0
0
0.2
0.4
0.6
0.8
1
1
2
3
4
5

The probable error in values of $H_c$ resulting from uncertainty in the calibration, is represented by the height of the squares. The contribution to this error due to the uncertainty of the true end of redistribution is not shown on the figure. This error was partly discussed in the last chapter and will be discussed further in the following section. The inconsistency in the data especially at very low saturations could be mostly the result of the subjectivity in identifying the true end of redistribution.

As shown in Figure 3, data from both methods appear to fit on a single smooth curve. This indicates that the water characteristic curve obtained by this new method has the same characteristics as the old curve and therefore such a curve could have the same applications as the traditional one. The data denoted by numbers are those for which data in the form of voltage as a function of time were collected during the redistribution period.

The fact that the voltmeter did not register a constant stable voltage at the end of a drainage step is shown in Figure 4. This figure shows the voltage history at 5 saturation points. These points are labeled in Figure 3. The vertical axis is the voltage registered on the voltmeter at any time. The horizontal axis is the time that the voltmeter was monitored. Note that during these transition periods the drainage had been stopped by closing the burette valve (Figure 1) and the soil system was under an external static condition.

Figure 4


Redistribution time at diff. saturation
Voltage (volt.)
10
9
8
7
6
5
4
3
2
1
0
40
80
120
160
200
240
Time (min.)
1
2
3
4
5

The voltmeter sensitivity was one millivolt. It is equivalent to less than 0.1 mm of water when converted to pressure head. This level of accuracy was more than adequate for the system under consideration. The time was also measured accurately with a stopwatch. Therefore the margin of error in the data shown in Figure 4 is probably less than 1% in all cases.

The main difficulty in analyzing the redistribution process is associated with the definition of redistribution time. It is the time required for the voltmeter to become "stable". As shown in Figure 4 the voltmeter drops to a final value asymptotically. Therefore, in a certain sense it will never become "stable" as it only becomes stable as $t \to \infty$.

Figure 4 shows that in some cases the rate of the drop is smaller and therefore it takes longer for the voltmeter to stabilize. One may conclude that the data determining the redistribution time and therefore the corresponding voltage at those cases are less accurate. Note that during the main experiment a long time was considered for the voltmeter stabilization at each point. The attempt was to capture the voltage drop as much as possible.

Figure 4 shows that at low saturations the redistribution process is slower. In other words, it takes longer for the system to come to an internal static condition. It seems that the low conductivity and relatively large drainage increment could cause the delay. On the other hand at high saturations,

especially with small drainage increments, it is on the order of minutes for the redistribution precess to take place. Again the high conductivity there, could be the main reason for this behavior.

The voltage drop, by itself, shows that the capillary pressure across the cell is dropping. Noting that a constant high air pressure was applied on top of the cell, Figure 4 reveals that the wetting phase pressure in the plate increases during the redistribution process. It confirms the physical analysis of the behavior of the system during the redistribution process presented in Chapter 2.

### 4.3. Moisture Profiles Within the Soil Samples

The data from seven experiments are shown in Figure 5. The vertical axis represents the height of the soil sample which was divided into three equal layers. Layers 1, 2 and 3 refer to the bottom, middle and top layers, respectively. Each moisture profile in this figure depicts the saturation of the various layers of a particular packed soil sample after it has been drained from 100% to around 50% saturation in one step.

As described before, three smaller samples were collected at each layer. It was observed that of all possible moisture profiles in a packed sample the vertical moisture profile was the dominant and more consistent one. Therefore, the average saturation of the three samples for each layer is shown in Figure 5. Saturation of the samples at each layer is provided

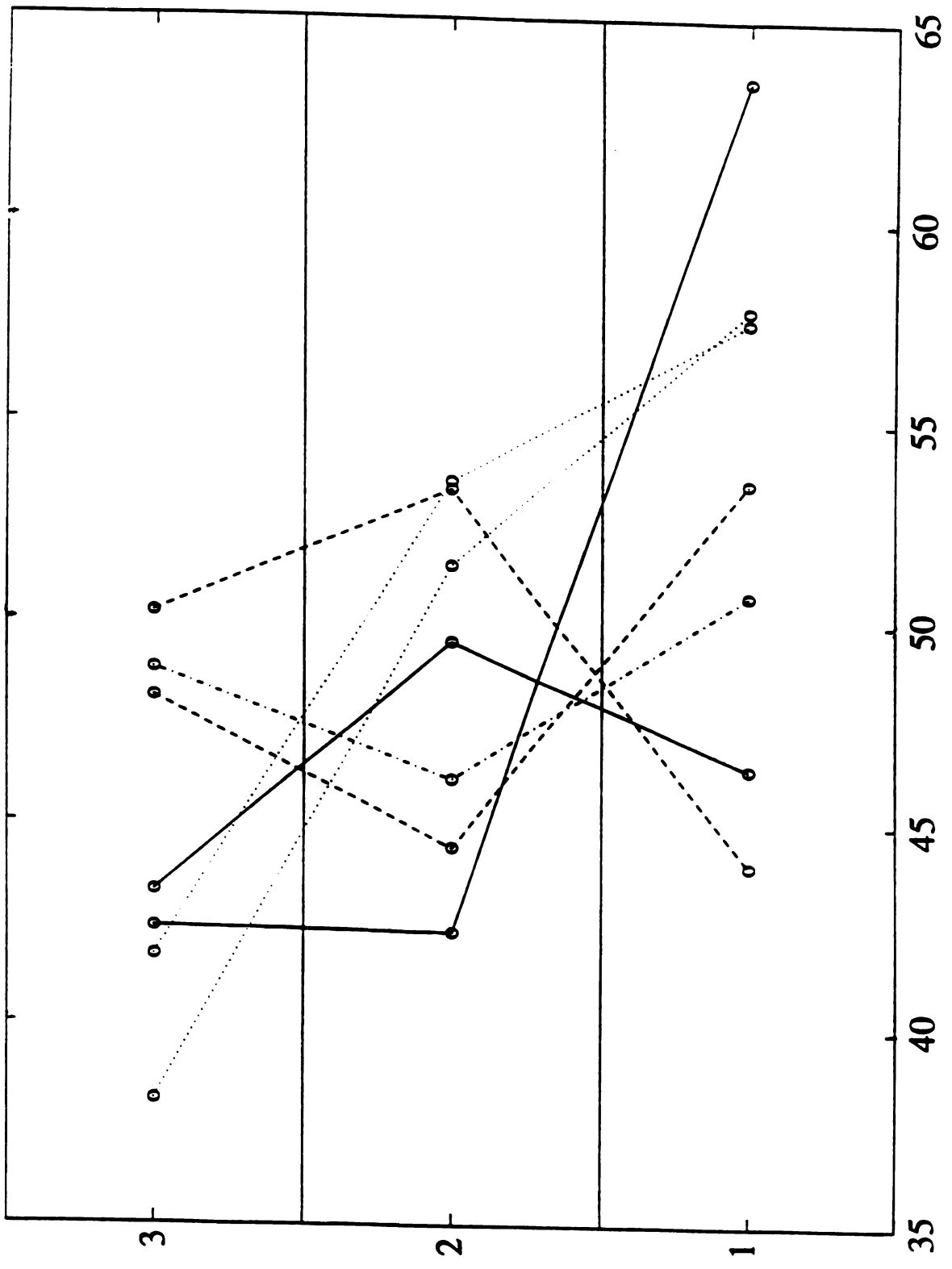



Figure 5

in the Appendix.

As mentioned earlier, an average of 5% of the mass of the soil sample was lost during the stratifying procedure. The average saturation error associated with the data shown in Figure 5 is ±0.8%. It was computed from the mass balance check at the end of each experiment by oven drying the samples. The layer's heights were chosen to be equal in each soil sample. The average error in layer height is ±3%.

To analyze the profiles shown in Figure 5 let us first discuss why some regions in a single sample have higher moisture contents than other regions. According to the physics of the flow, the drainage will first occur locally along the path of least resistance. This path possibly includes the biggest pores that are filled with the wetting phase at the time. It is reasonable to believe that in a packed soil sample these paths and pores are located randomly.

By the above analysis the inconsistency between the saturation profiles of different samples, shown in Figure 5, could be rationalized. The profiles in this figure reveal that the drainage process within different samples occurs preferentially from different regions. These regions seem to be located in the samples without any consistent order. The reason could be the fact that each packed soil has randomness with regard to positioning of the pores and the least resistant paths. It is a microscopic property of a particular packed soil and can not be repeated by following the same

macroscopic packing procedures.

### 4.4. Influence of the Hydraulic Gradient on the Drainage and Redistribution Times

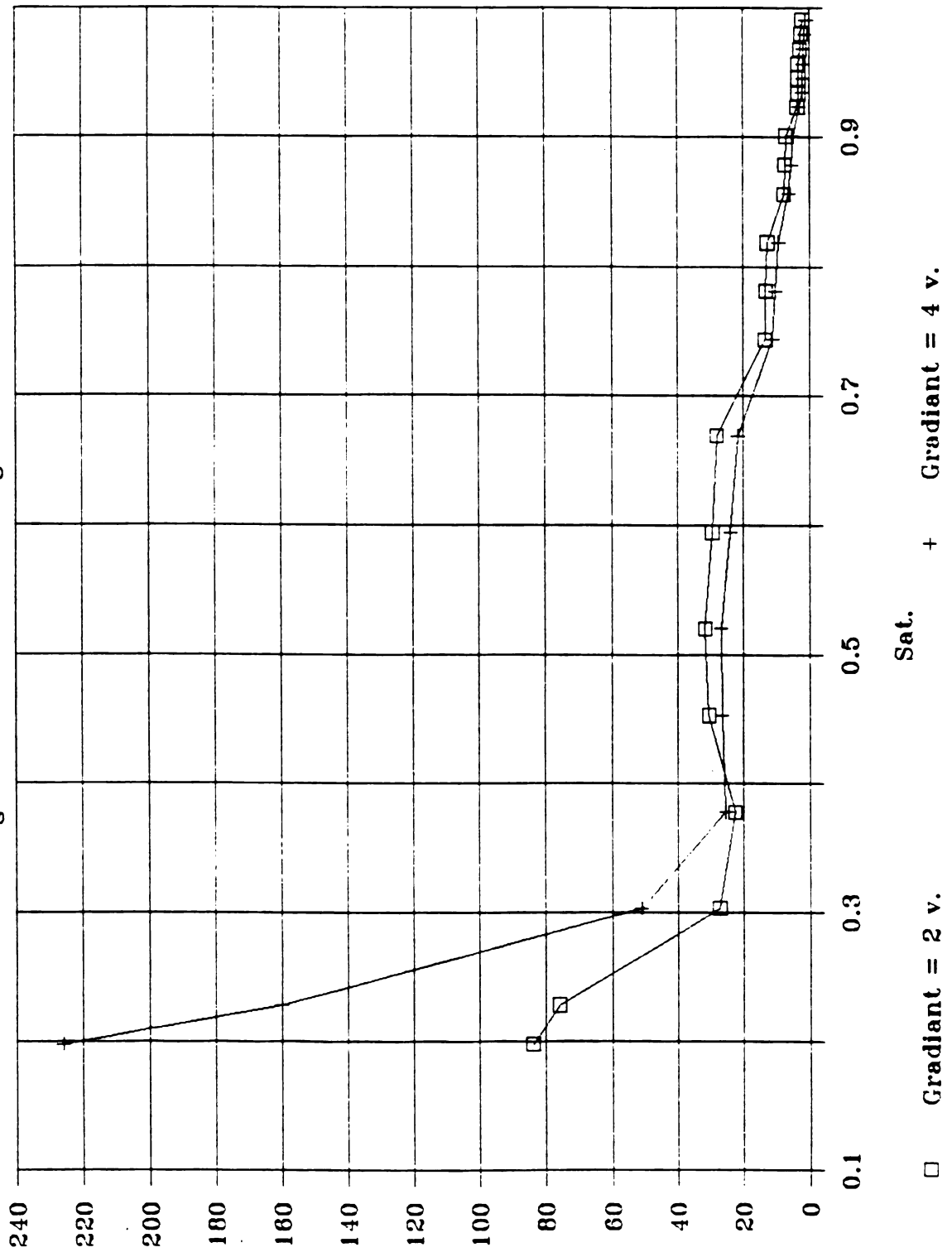
Figure 6 depicts the results of the experiments on the drainage process. They measured the drainage time for equal drainage increments under two different hydraulic gradients. They were performed on two different samples. Hydraulic gradients are given in volts which can be converted to the differential pressure head using the calibration curve. The time to drain the sample from a higher to lower saturation has been plotted at the lower saturation on the vertical axis.

Drainage time was measured accurately using a stopwatch which recorded time to the nearest hundredth of a second. The saturation was monitored by the burette. The maximum error in saturation due to propagation of the burette reading error was ±0.5%. The mass balance was checked at the end of the experiment by oven drying the sample. The measured error was -2% saturation. The loss was probably due to Soltrol that remained on the surface of the cell.

As shown in Figure 6, at high saturations the wetting phase will drain out more quickly under higher gradients. This is consistent with the expectation based on Darcy's equation presented earlier. At high saturations an average conductivity could be assigned to the entire sample. Then, neglecting conductivity variation over time and space, the drainage flux

Figure 6

Drainage time under different gradients



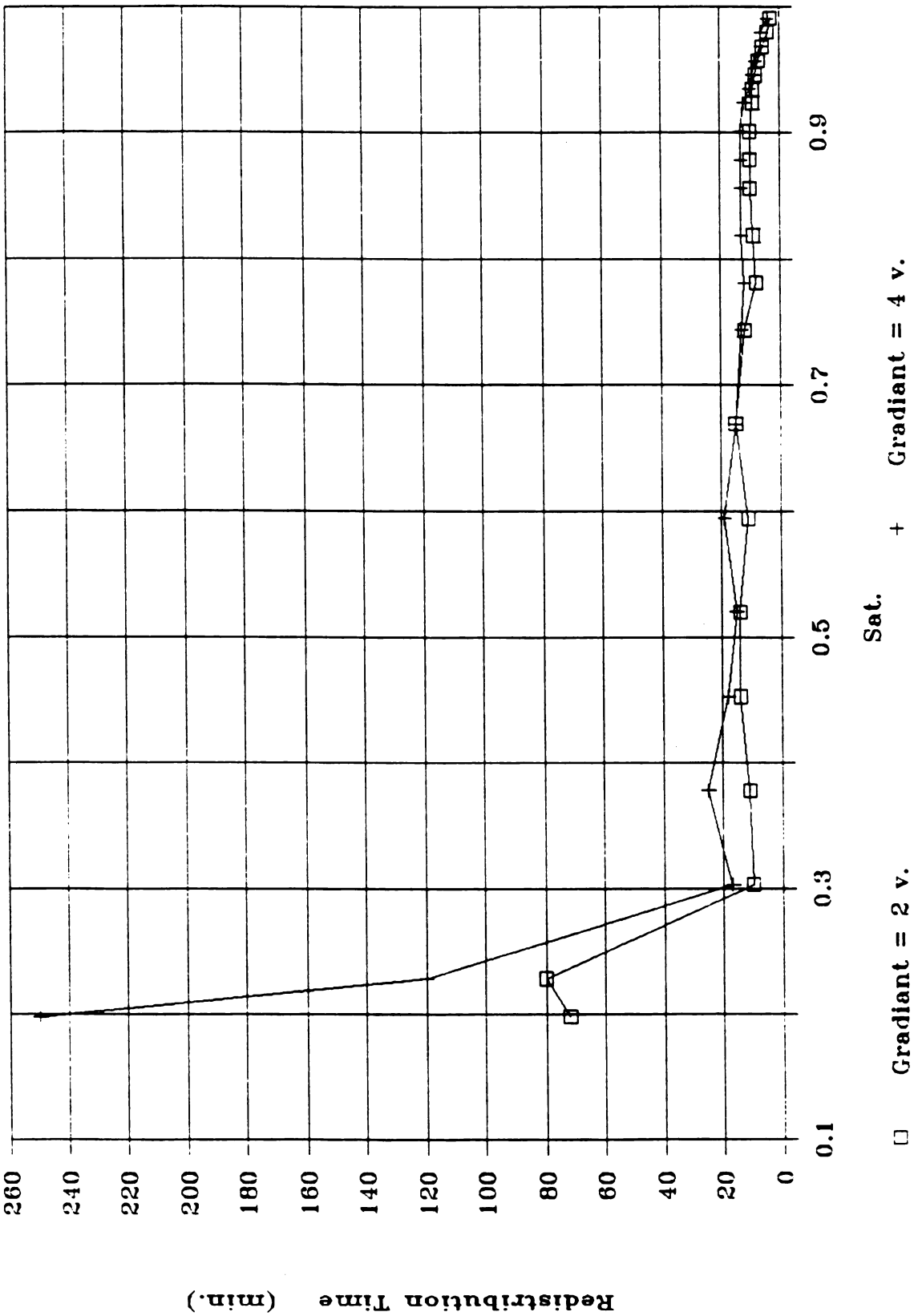
out of the sample is directly proportional to the hydraulic gradient.

At low saturations, however, Figure 6 shows that the higher gradient retards the drainage process. The reason could be explained by considering conductivity variations inside the sample. As discussed earlier, drainage occurs in some regions of the sample first. Applying a high gradient could desaturate these regions considerably. Therefore conductivity of the sample would locally drop to a low value. Further drainage from the sample may require flow of the wetting phase through this region. In this situation the low conductive region would delay the overall flux out of the sample.

Results from the experiments investigating the redistribution time are depicted in Figure 7. The figure shows the results on two packed soil samples each drained under a different hydraulic gradient. The vertical axis shows the redistribution time. The saturation of the sample is on the horizontal axis. Since the redistribution occurs when a fixed saturation exists in the sample, unlike in the case of drainage time, the redistribution time is assigned to a saturation point.

The packed soil samples used in this last study were those used to develop Figure 6. The drainage and redistribution times were recorded on the same samples in a single run. Therefore, the errors associated with the measurements of the time and saturation are the same as

Figure 7


Redistribution time under two gradients
Redistribution Time (min.)
260
240
220
200
180
160
140
120
100
80
60
40
20
0
0.1
0.3
0.5
0.7
0.9
Sat.
□ Gradiant = 2 v.
+ Gradiant = 4 v.

discussed with regard to Figure 6. However, the determination of the redistribution time has an inherent uncertainty due to its indeterminate character by definition. This was discussed earlier in the last section.

In Figure 7 for saturations greater than 30%, data for the two gradients can not be significantly distinguished from one another due to the margin of error associated with each one. However, since the redistribution time measurements were conducted consistently throughout the experiment, one may draw a conclusion from those data. For example, it may be interpreted that the higher gradient causes a longer redistribution time, in general. At low saturation, the higher gradient causes such a longer redistribution time that the conclusion is obvious and undoubted.

The behavior of the system during redistribution (Figure 7) may be deduced from Darcy's equation in a similar way to what was done with regard to drainage (Figure 6). The only difference is that the drainage is a process in which the wetting phase flows out of the soil sample where the redistribution process considers internal flow of the wetting phase. However, both processes are governed by the same concepts and equations.

Note that the drainage increment may have an effect on the drainage and redistribution time under any gradient. This effect was not considered in this study.

# CHAPTER 5

# CONCLUSION AND RECOMMENDATION

## Conclusions:

- Consistent results could be obtained by the new method by applying the explained procedures.
- Water characteristic curves obtained by the new method agree with the traditionally generated data.
- By using more controls, this method generates more reliable results more easily, compared to previous methods. The controls include valves to set the saturation, a pressure transducer to track $P_c$, and capability to alter the hydraulic gradient.
- The new method could require less overall time to generate $P_c(S)$ curves, by using the controls.
- Very accurate measurements of capillary pressure are made by using a sensitive pressure transducer.
- The method establishes the external and internal static equilibrium conditions at two separate stages.
- Once the external static condition is imposed on the system,an internal moisture profile exists inside the soil sample that may not be at static equilibrium condition.
- The exact shape of such profile may depend on the internal structure of the sample and may not be reproducible through same packing procedures.
- The method requires a waiting period for the internal moisture to redistribute. Redistribution of moisture inside the sample is necessary for establishing the internal static equilibrium condition.

- The hydraulic gradient causing the internal redistribution of moisture drops to zero asymptotically.

- Other things being equal, the redistribution time is longer at lower saturations.

- Results show that at lower saturations, the higher hydraulic gradient retards both the drainage and redistribution. At higher saturations the higher hydraulic gradient makes the drainage and redistribution occur faster.

- The drainage and redistribution times may also depend on the drainage increments.

Recommendations for future work:

- Get the entire $P_c(S)$ curve by the new method several times. Look for reproducibility of the curve.

- Determine the internal moisture profile at the end of drainage without destroying the soil sample. Look for reproducibility of the profiles.

- Try several hydraulic gradients to monitor the drainage and redistribution times at different saturations. Look for the optimum gradient at every saturation.

- Apply suction on top of the burette to drain the sample. Look for any difference in the drainage and redistribution times compared to applying air pressure on top of the cell.

- Numerically simulate the drainage and redistribution processes. Compare the internal moisture profile at the end of drainage and also the drainage and redistribution times to experimental results.

- Look at the effect of drainage increment on the overall time to generate $P_c(S)$ curves.

# APPENDIX

## APPENDIX

During the course of the experiment, the valves and manometer were placed in the system and positioned so that the set up could function for both the experiment and transducer calibration (Figure 1). The positioning of the valves is discussed in the set up and procedure section.

Figure A-1 shows two different calibration curves one obtained before and one obtained after an experiment that lasted two days. Pressure head difference across the transducer, in centimeters of water is shown on the vertical axis and the output voltage on the horizontal axis. Each calibration curve was obtained by increasing air pressure from zero to maximum and decreasing it back to zero in a step wise manner.

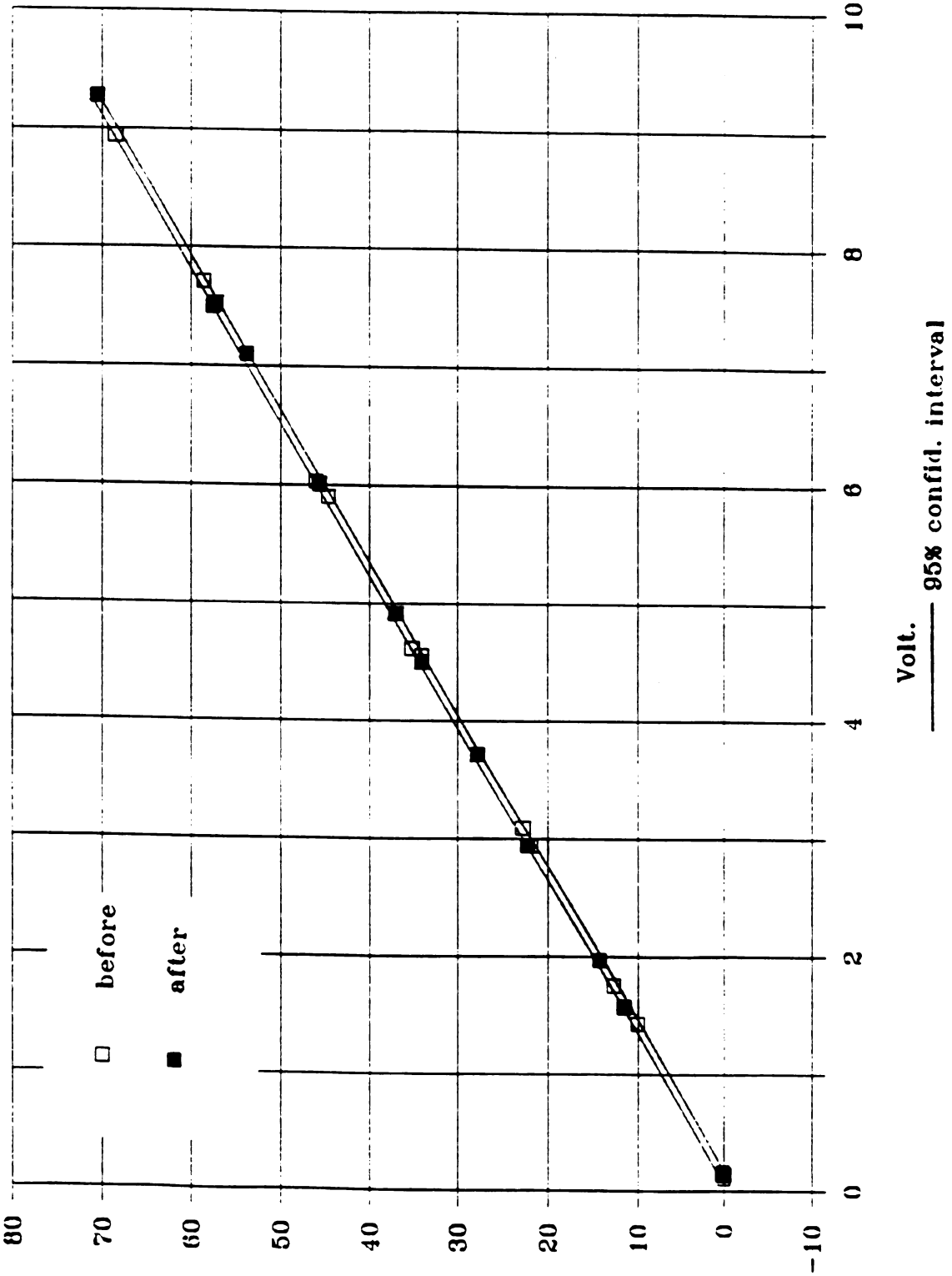
The method of least squares was used to fit a straight line to the data. Based on that, the equation for the 95% confidential interval is:

$$H_c = -.854 + 7.735\ V \pm 0.458$$

where, V is output voltage, and $H_c$ is the capillary pressure

Figure A-1

Calibration Curves



head in cm of water. This interval is shown on Figure A-1.

Figure A-1 suggests that basic properties of the transducer remained constant over this two day period. The transducer was recalibrated for each experiment to account for small amounts of drift.

**Part List:**

- Aluminum cell was made at the Research Complex-Engineering Machine shop
- 5/8" x 1/4", 1 Bar High Flow Ceramic Plate (Part No. 604D02-B1M3 Soil Moisture Equipment Corp. Santa Barbara, CA.)
- Viton O-ring (National O-rings Company, Detroit Ball Bearing, Lansing, MI)
- 0.062" ID x 1/8" OD Teflon Tube (Upchurch Scientific Inc., Oak Harbor, WA)
- Variable Reluctance Pressure Transducer, Model No. CJVR (C.J. Enterprises Tarzana, CA)
- Carrier Demodulator Model No. CJCD-2061 (C.J. Enterprises Tarzana, CA)
- Bench Digital voltmeter (Part No. 8050A John Fluke MFG. Co. Plymouth, MI)
- 3-way Ball Valve Model No. 2Z-B2XJ-SSP (Parker Hannifin Corp., Instrumentation Valve Division, Jacksonville, AL)
- Air Valve (Three-way stopcock, Chemistry shop at MSU, E.Lansing, MI)
- Soltrol 170 Cat. No. AP1700 (Phillips 66 Company, Borger, TX)
- 25 ml. Burette with stop cock (Chemistry shop at MSU, E.Lansing, MI)

Experiments to determine the moisture profile at the end of drainage

| | | Experimental Run | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Top Layer | Sample 1 | 40.7 | 36.1 | 40.4 | 49.4 | 39.9 | 48.5 | 39.0 |
| | Sample 2 | 40.7 | 48.5 | 46.7 | 47.2 | 43.0 | 48.5 | 41.3 |
| | Sample 3 | 48.4 | 55.0 | 37.5 | 50.1 | 44.3 | 53.5 | 34.8 |
| Mid.Layer | Sample 1 | 47.4 | 42.8 | 55.3 | 43.5 | 45.7 | 56.2 | 47.3 |
| | Sample 2 | 56.1 | 45.7 | 57.4 | 49.3 | 41.7 | 51.7 | 54.2 |
| | Sample 3 | 45.0 | 44.5 | 47.5 | 45.7 | 39.3 | 52.1 | 52.2 |
| Bot.Layer | Sample 1 | 47.8 | 51.8 | 56.4 | 54.1 | 56.0 | 39.5 | 62.9 |
| | Sample 2 | 46.5 | 57.4 | 57.2 | 50.4 | 65.9 | 44.3 | 57.0 |
| | Sample 3 | 44.8 | 51.6 | 59.2 | 46.9 | 69.4 | 49.0 | 52.3 |

# PRESSURE TRANSDUCER
## VARIABLE RELUCTANCE--- MODEL CJVR

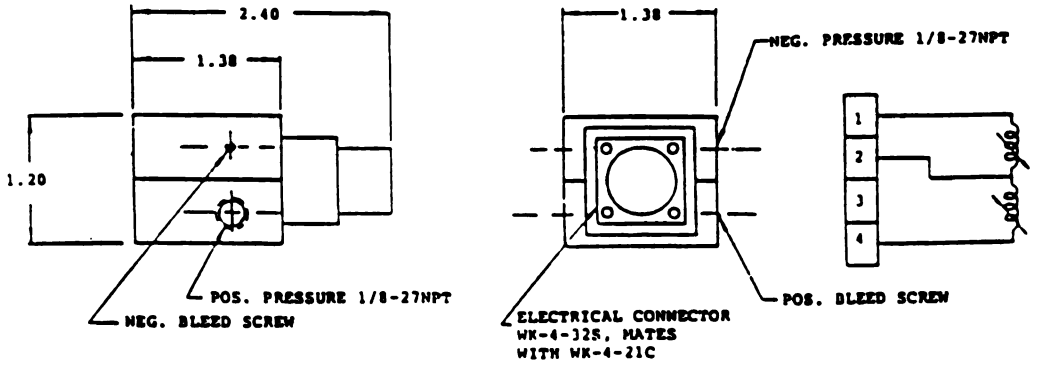
* RANGES OF 0.1 TO 500 PSIG & PSID
* ACCEPTS CORROSIVE LIQUIDS & GASES
* LOW VIBRATION & SHOCK SENSITIVITY
* HIGH NATURAL FREQUENCY

DESCRIPTION

The Model CJVR Variable Reluctance Pressure Transducer is designed to measure low and medium gage and differential pressures. In typical AC excited bridge circuits, the system provides a full scale output of approximately 25 millivolts per volt input at 5KHz. The transducer will operate with most carrier systems operating at a frequency between 3KHz and 10KHz. With C.J. carrier demodulators CJCD and most Pace carrier systems, the transducer will deliver a 0 to ±5VDC or ±10VDC output. Constructed primarily of 400 series stainless steel, the transducer consists of basically of a flat pressure sensing diaphragm (field replaceable) clamped between two matched case halves each containing electrical pickoff coils. Applied pressure deflects the diaphragm which is detected by the two pickoff coils. When the coils are connected as two opposing legs of a bridge circuit, the resultant bridge output is proportional to pressure. The pickoff coils are hermetically sealed in the case so as to isolate them from the pressure media. Bleed screws are provided in both case halves to facilitate complete liquid filling for dynamic measurements.

SPECIFICATIONS

| | |
|---|---|
| RANGES: | 0.1 to 500 psi gage & differential |
| LINEARITY: | ±1/2% full scale (best fit straight line) |
| HYSTERESIS: | 1/2% full scale |
| OVERPRESSURE: | 2 times range with 1/2% F.S. maximum zero shift |
| LINE PRESSURE: | 25 times range or 500 psi, whichever is less |
| OUTPUT: | 25 mv/V nominal @ 5KHz |
| INDUCTANCE: | 10 mh/coil nominal @ 5KHz, zero balance within 20% F.S. |
| PRESSURE MEDIA: | Corrosive liquids & gases both sides compatible with 400 series stainless steel, Buna "N" and silver |
| TEMPERATURE: | Operational from -65° to +250°F. Compensated from 0° to +170°F. with nominal deviation from 70°F. calibration of 3% F.S. |
| PRESSURE CAVITY: | $4 \times 10^{-3}$ cubic inches |
| VOLUMETRIC DISPLACEMENT: | $4 \times 10^{-4}$ cubic inches |
| WEIGHT: | 15 ounces |




C. J. ENTERPRISES
division of C. J. Instruments, Inc.
P. O. BOX 834 TARZANA, CA 91356 (818) 996-4131

# CARRIER DEMODULATOR
# FOR VARIABLE RELUCTANCE TRANSDUCERS
# MODELS CJCD-4111, CJCD-4111M, AND CJCD-4111D

## FEATURES

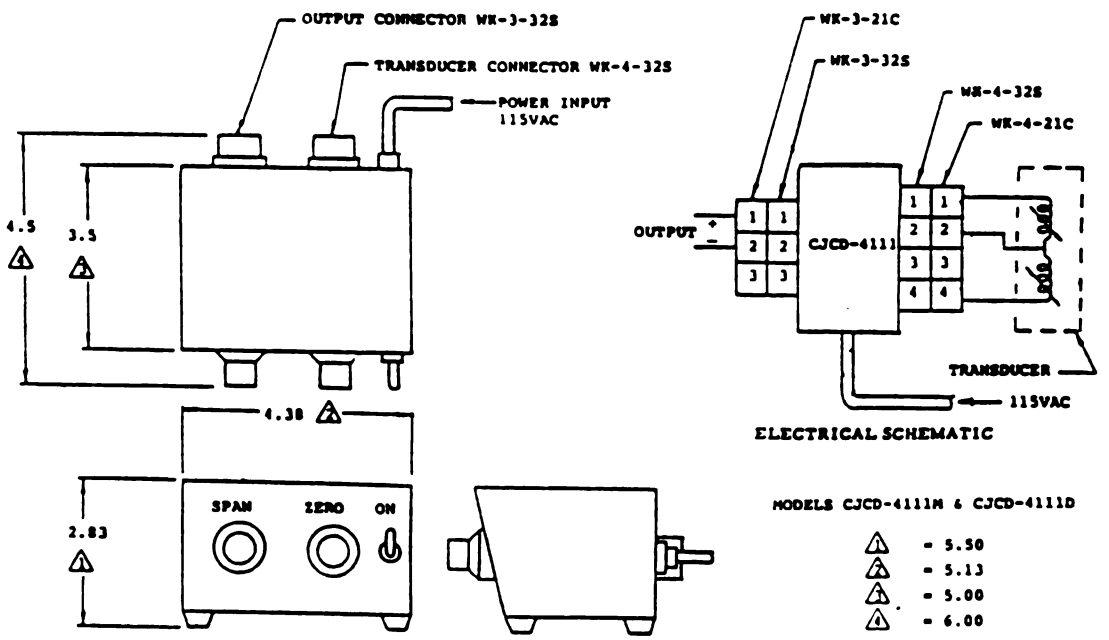
* 115VAC INPUT
* UP TO ±10VDC OUTPUT
* SMALL RUGGED CONSTRUCTION
* OPERATES WITH C.J. & PACE TRANSDUCERS

## DESCRIPTION

The Model CJCD-4111 Carrier Demodulator, designed for operation on unregulated 115VAC, 60Hz, operates with C.J. and Pace variable reluctance transducers to provide up to 0-10 or ±10VDC full scale output for voltage controlled telemetry and other DC systems. Excitation of 8 volts pk-pk at 4 KHz is applied to a bridge including the two inductance arms of the transducer. A solid-state amplifier and demodulator converts the bridge output to DC. Response time is less than 50 milliseconds. The assembly is packaged in a small lightweight aluminum housing with external digital turns-counting dials for zero and span control. Models CJCD-4111M and CJCD-4111D are the same as the basic Model CJCD-4111 except the CJCD-4111M incorporates a dial indicating readout and the CJCD-4111D incorporates a digital readout.

## SPECIFICATIONS

| | |
|---|---|
| POWER REQUIREMENTS: | 115VAC, 60 Hz (specials available for DC operation) |
| REGULATION: | Better than 0.2% from a voltage level of 105 to 125VAC at frequencies from 50 to 70Hz. |
| OUTPUT: | Full scale is adjustable from ±1VDC to ±10VDC into a 1000 ohm load or greater with a 10 turn digital turns counting dial. |
| ZERO: | Adjustable up to ±75% of full scale with a 10 turn digital turns counting dial. |
| RESPONSE: | Less than 50 milliseconds. |
| ACCURACY: | Better than ±0.5% F.S. including linearity & drift. |
| TEMPERATURE: | 32°F. to 160°F. |
| THERMAL EFFECT: | 0.03% F.S./°F. maximum. |
| WEIGHT: | 24 ounces |

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