

3.3 Water Retention and Storage

3.3.1 Introduction

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The relation between soil water (actually soil solution) content and matric potential is a fundamental part of the characterization of the hydraulic properties of a soil (Klute, 1986). This relation is referred to by various names, such as *water retention curve*, *water characteristic curve*, *water content–matric potential curve*, and *capillary pressure–saturation relation*. The function relates a capacity factor, the water content, to an intensity factor, the energy state of the soil water. The energy state is expressed by names such as *suction*, *tension*, *capillary pressure* or *capillary pressure head*, *soil water pressure head*, and *matric head*. For unsaturated soils, values for suction, tension, and capillary pressure (head) are positive, while those for matric head are negative. We adopt the viewpoint that the soil water matric head is the result of pressure and adsorptive forces. If clay particles are present, the adsorptive forces include osmotic forces due to the high concentration of cations in the diffuse double layer. For a more complete description of forces acting on soil water, and their related potentials, one is referred to Koorevaar et al. (1983) and Tuller et al. (1999). The Young and Laplace equation, which relates the pressure difference, ΔP , across the gas–liquid interface in a unsaturated porous medium to the mean radius of curvature (Adamson, 1982; Kirkham & Powers, 1972; Corey, 1994), r_c , can be expressed as

$$\Delta P = (2\sigma)/r_c = (2\sigma\cos\beta)/r = P_w - P_a \quad [3.3.1-1]$$

where σ is the surface tension (N m^{-1}), β is the contact angle between the liquid and the solid phase, r is the maximum liquid-filled pore radius (m) for the unsaturated soil (by convention $r < 0$ if the radius of curvature is in the gas phase), P_w is the water pressure (Pa), and P_a is the air pressure (Pa). Outside the region of influence of the adsorptive forces the matric head, h_m (m), is defined by

$$h_m = \Delta P/(\rho_w g) \quad [3.3.1-2]$$

where ρ_w is the density of water (kg m^{-3}) and g is the gravitational field strength (N kg^{-1}). It should be noted that Eq. [3.3.1-2] no longer applies if the water molecules are under the influence of adsorptive forces, that is, when water exists as thin films attached to the solid surfaces of the soil particles. In this case, h_m is the result

of the negative adsorptive potential and the positive pressure potential (Eq. [3.3.1–1] still applies across the gas–liquid interface). Our measurement techniques, however, do not distinguish between pressure and adsorptive forces, and the methods as described in this chapter always yield h_m , whether adsorptive forces play a role or not. It should also be noted that under normal field conditions $P_a = 0$ (atmospheric pressure). If fluids other than air and water are present, h_m can still be calculated from the above equations using appropriate values for the different variables (see Chapter 7 for additional information).

The potential of soil water may be expressed in units of energy per unit mass (J kg^{-1}), energy per unit volume (N m^{-2} or Pa), or energy per unit weight (m). For most soil water applications, the use of energy per unit weight, referred to as *head*, is most convenient because it results in units of length. The matric head is thus expressed as the height of a fluid column of a given density. The fluid is usually water at the ambient temperature of the soil water system.

Soil water (solution) content may be expressed on a weight basis (gravimetric water content, kg kg^{-1}), a volume basis (volumetric water content, θ , $\text{m}^3 \text{m}^{-3}$), or a degree of saturation basis (volumetric water content divided by the porosity, S). For the analysis of water flow in soil profiles, the use of volumetric water content is most convenient.

The need for knowledge of the water retention relation comes about for various reasons. In part, the soil water retention curve characterizes the soil type from which pore-size distribution (Section 3.3.4) and water holding capacity properties (Section 3.3.3) can be derived. In many other cases, the soil water retention relationship must be known to solve the Richards (1931) equation for unsaturated water flow. Specifically, we need the slope of the soil water retention curve, or water capacity, $C(h_m)$ (m^{-1}), defined as

$$C(h_m) = (d\theta)/(dh_m) \quad [3.3.1-3]$$

The soil water capacity is always greater than zero, since a decreasing matric head is associated with a decreasing θ , corresponding to the drainage of smaller-sized pores (Eq. [3.3.1–1]).

In concept, the methods presented in Section 3.3.2 require that the retention data are obtained with the soil water at hydrostatic equilibrium; that is, at any time at which a data pair (h_m, θ) for the water retention curve is obtained, it is assumed that the soil water is at rest and the local soil water has adjusted to the changing curvature of the gas–liquid interface. However, one must be aware that hydrostatic equilibrium is not always attainable. An example of nonequilibrium behavior may be found in the application of the pressure plate extractor (Section 3.3.2.4) with applied gas pressures exceeding 100 kPa (1 bar). It is conceivable that the unsaturated hydraulic conductivity, $K(\theta)$, of certain soils may be so low that drainage rates become undetectable, hence making it difficult to ascertain hydrostatic equilibrium unless local soil water matric head values are measured. Eching and Hopmans (1993) concluded that soil water retention curves using the pressure cell method (Section 3.3.2.3) could be significantly affected by the applied gas pressure, especially for coarse-textured soils, even for gas pressures of about 10 kPa.

The water retention curve is very much dependent upon the particle-size distribution, which determines the soil texture, and the arrangement of the solid particles, which is referred to as the *soil structure* (Salter & Williams, 1965; Richards & Weaver, 1944; Reeve et al., 1973; Sharma & Uehara, 1968; Croney & Coleman, 1954; Chapter 2). Organic matter content and the soil water composition also play a role in the shape of the water retention curve. Organic matter affects the shape of the retention curve directly because of its ability to adsorb water, and indirectly because of its effect on soil structure. Water retention curves of soils that contain swelling clay minerals are affected by the amount and composition of solutes present in the liquid phase (Dane & Klute, 1977).

Besides this introduction (Section 3.3.1), Section 3.3 consists of four additional sections. In Section 3.3.2, proven laboratory methods to determine soil water retention data are described. Section 3.3.3 describes how a number of field properties can be determined in situ or from laboratory determined data. In Section 3.3.4, an overview of the theory and application of established parametric models to fit measured water retention data is presented. Finally, in Section 3.3.5, the concept of property-transfer models is explained and applied to derive retention data from other physical properties.

3.3.1.1 References

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3.3.2 Laboratory

3.3.2.1 Introduction

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3.3.2.1.a General

The traditional way of determining the water retention relation involves establishing a series of equilibria between water in the soil sample and a body of water at a known potential. The soil water system is in hydraulic contact with the body of water, usually via a water-wetted porous plate or membrane. At each equilibrium, the volumetric water content, θ , of the soil is determined and paired with a value of the matric head, h_m , determined from the pressure in the body of water and the gas phase pressure in the soil. Each data pair (θ , h_m) is a point on the retention relation. Data points can be obtained during drainage of water from the sample or during imbibition of water into the soil. Unfortunately, the two relations thus obtained will be different; that is, the water retention relation is hysteretic and the water content during drainage will be greater than during wetting for a given value of the matric head (Topp, 1969; Haines, 1930; Pavlakis & Barden, 1972). The principal features of hysteresis in the retention relation are shown in Fig. 3.3.2-1. The drainage curve that starts at complete saturation of the porous medium is the initial drainage curve (IDC). As water is removed from a porous medium, the matric head decreases (i.e., it be-

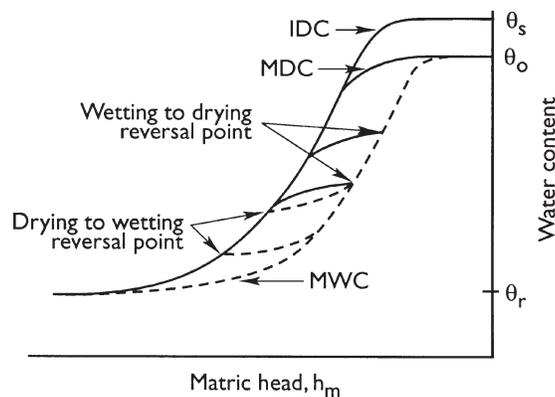


Fig. 3.3.2-1. Diagram of hysteresis in the water retention function of a coarse-textured soil of stable structure. Drying curves are shown as solid lines; wetting curves as dashed lines. IDC denotes the initial drying curve, MWC the main wetting curve, and MDC the main drying curve. The lines between the MDC and MWC represent scanning curves.

comes more negative), and the water content approaches a limit called the residual water content, θ_r (often a curve fitting parameter; see Section 3.3.4). At this point the hydraulic conductivity of the soil has, for most practical purposes, become zero, and further drying of the sample can only be accomplished by evaporation. The main wetting curve (MWC) is obtained by wetting the soil from θ_r . As the soil is wetted along the MWC and the matric head approaches zero, the water content approaches a value, θ_0 , which is less than the porosity of the soil due to air entrapment. Usually θ_0 is about $0.85\theta_s$ (θ_s is the saturated water content; i.e., all pores are filled with water). The water content θ_0 is often referred to as the natural saturation or the saturated water content. The drainage curve obtained beginning at θ_0 is called the main drainage curve (MDC). It merges asymptotically with the IDC as h_m decreases. An infinite number of scanning curves lies inside the envelope of the MDC and MWC. A few are shown in Fig. 3.3.2-1. The particular scanning curve applicable in a given situation depends on the sequence of reversal points that has occurred during drying and wetting of the soil. The existence of hysteresis complicates the modeling of soil water movement. Mualem (1974) and Mualem and Dagan (1975) have developed methods for calculating the scanning curves from the MDC and the MWC and knowledge of the reversal points. Their methods can be incorporated into numerical models (Section 3.3.4.10).

Soil water retention data pairs are most often determined step-wise, waiting until static equilibrium has been reached at each step. It has been demonstrated, both experimentally and via theoretical analysis (Davidson et al., 1966), that water retention data may be influenced by the rate and/or pressure step size at which they are being obtained.

3.3.2.1.b Samples

Soil samples for determining retention curves consist of either repacked, disturbed soil material or undisturbed samples. Before packing, the disturbed soil is often dried and passed through a 2-mm sieve. Since the structure of the soil affects the water retention, especially in the low suction range, it is generally best to use samples of undisturbed nature. Repacked samples are often used for more basic laboratory studies. A number of devices are available for obtaining relatively undisturbed soil samples (e.g., Section 2.1), such as manually operated drop hammer samplers or hydraulically operated sampling devices, which can be mounted on the back of a pickup truck, tractor, or small trailer. Methods of procuring undisturbed samples were discussed by McIntyre (1974).

The sample dimensions will generally be in the range of 5 to 8 cm in diameter and 1 to 6 cm in height. The time for reaching equilibrium is proportional to the square of the height of the sample (Section 3.3.2.7.d). To minimize the equilibration time, the height should therefore be kept relatively small, but not so small that the samples cannot be handled properly. A practical height for many purposes is 2 to 3 cm. If samples with larger heights are used, corrections can be made as outlined in Section 3.3.2.10. The diameter and height of the sample should be large relative to the size of the structural units (e.g., peds, cracks, worm and root holes, aggregates) over which the retention data are to be averaged.

Soil in situ is subjected to an external load due to the weight of overlying soil. In swelling soils, the external load on the sample affects the water retention curve

(Collis-George & Bridge, 1973; Philip, 1969; Dane & Klute, 1977). When such soils are studied, consideration should be given to a method of applying, measuring, and controlling the external load on the soil sample. Equipment for determining water retention of swelling soils is not well developed for routine use on large numbers of samples. Garnier et al. (1997) discussed the simultaneous determination of hydraulic properties and a shrinkage curve of a swelling soil by evaporation.

In some cases, it may be desirable to obtain water retention data on soil that is to be used in studies of various transport processes in a laboratory setting. In such cases, the use of packed samples may be entirely appropriate. One should keep in mind, however, that packed soils will never be entirely representative of soils in situ, because even coarse-textured soils may exhibit structural features such as root and worm holes.

3.3.2.1.c Sample Preparation

If undisturbed soil samples are to be stored for extended periods of time at their field water content, it is best to add a few drops of propylene oxide to each sample, cap them, and then store them in a refrigerator. This will prevent bacterial growth and the resulting formation of excretions (slime) that may affect the shape of the retention curve. It is important that the ends of the cores are trimmed flat prior to testing.

If cores are to be packed to a predetermined bulk density, the following procedure is suggested (Klute, 1986; Fig. 3.3.2-2):

1. Place enough soil to pack the desired number of cores in a plastic bag. Add sufficient water to the soil to make it slightly cohesive. A gravimetric water content (mass of water divided by mass of oven-dry soil) of about 0.05 is generally suitable for sands, while 0.08 to 0.1 is suitable for soils of finer texture. Close the bag to minimize evaporation and mix the soil thoroughly three to five times over a period of 2 to 3 d to allow the water to redistribute throughout the soil. Determine the gravimetric water content of the soil in the bag from three to five random samples. From the volume of the sample ring, V_s (m^3), the desired bulk density, ρ_b (kg m^{-3}), and the gravimetric water content, w (kg kg^{-1}), the required soil mass, M (kg), to fill the sample ring to the desired bulk density, can be calculated from:

$$M = \rho_b(1 + w)V_s \quad [3.3.2-1]$$

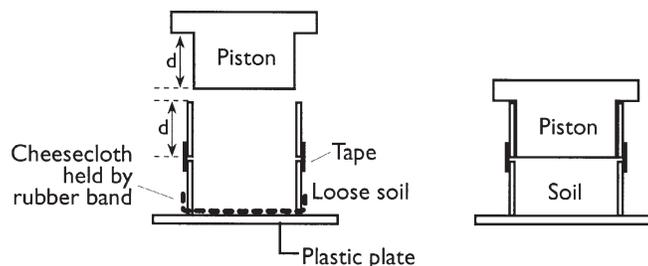


Fig. 3.3.2-2. Piston for packing cores to a given bulk density.

2. Tape a second cylinder (piston ring) to the top of the sample ring.
3. Fasten a piece of cheesecloth with a rubber band to the bottom of the sample ring.
4. Place the attached cylinders on a flat, sturdy surface, and pour the required amount of soil into the rings.
5. Insert the packing piston into the piston ring and compress the soil into the sample ring with a hydraulic press or by dropping the piston into the piston ring until the soil is flush with the top of the sample ring.
6. Remove the piston ring and set the sample ring aside until ready for analysis.
7. Repeat Steps 2 through 6 for as many sample rings as needed.

If a predetermined bulk density is not required, as is often the case in basic laboratory studies, other packing procedures are available. For example, if complete saturation is required, packing may be done by filling the sample ring incrementally under water (Oostrom, 1991). This method is mainly limited to sands. It requires mechanical stirring of the incremental layers to obtain a homogeneous porous medium. Sample rings may also be packed incrementally with dry soil. As with the under water packing, each additional layer should be well mixed with the previously added soil.

For longer cylinders, a packing procedure as outlined by Dane et al. (1992) may be used. Their apparatus to fill long cylinders consists of a clear plastic fill tube with an outside diameter slightly smaller than the inside diameter of the cylinder to be filled, and a large funnel that is attached to the top. The funnel should be large enough to contain all of the soil needed to fill the cylinder. A stopper placed in the opening of the funnel spout prevents the soil from flowing out prematurely. The bottom of the fill tube contains four sets of parallel wires. Each set is oriented 45° from the one above and/or below it. The purpose of the wires is to reduce the kinetic energy of the soil particles, allowing them to exit the tube with approximately the same amount of energy during the entire filling of the cylinder in a more or less random manner. To accomplish this, the fill tube is first lowered into the cylinder. Next, the stopper in the funnel spout is pulled out, allowing the soil particles to fall, while the tube is simultaneously pulled up with a winch-pulley system at a rate to maintain a distance of 5 cm between the bottom of the fill tube and the top of the soil surface inside the column. It is also advised that the column be tapped during the filling process.

3.3.2.1.d Wetting Solution

The chemical composition of the wetting fluid can affect the water retention of the samples, particularly in fine-textured soils that contain significant amounts of swelling clays. In coarse-textured soils, little attention needs to be paid to the chemical make-up of the wetting liquid. Generally a fluid with a chemical composition similar to that of the indigent soil water should be used. However, this composition is usually unknown.

A deaerated 0.005 *M* CaSO₄ solution is suggested as a general test liquid. Wetting with distilled or deionized water or freshly drawn tap water is not generally recommended. The former promotes dispersion of the clays in the sample, and the

latter is often supersaturated with dissolved air that may come out of solution after wetting the samples, causing the water content at a given pressure head to be affected. Due to the time duration over which a retention curve is determined, it is recommended that bacterial growth be inhibited by the addition of trace amounts of mercuric chloride and thymol to the wetting solution. These chemicals have a minimal effect on the surface tension of the soil solution when present in low concentrations. Special arrangements may be required to dispose of solutions containing toxic chemicals.

3.3.2.1.e Sample Wetting

The method of wetting depends on whether points on the IDC or the MDC are to be determined (Fig. 3.3.2-1).

If points on the MDC are to be determined, place the sample on top of a porous plate or membrane in the apparatus to be used to determine the water retention curve. Next, connect the outflow assembly to a source of wetting solution and let the water imbibe from the bottom of the soil sample. Slowly raise the external solution level to the near top of the sample ring. Once the wetting solution has wetted the surface of the soil, the sample can be assumed to be satiated. This process may take from several hours to many days, depending on the type of soil. It is important to remove all air from underneath the porous plate, as air may impede the wetting and/or drainage process.

If points on the IDC are desired, a vacuum wetting procedure to attain complete saturation must be used. It is preferred that the soil sample plus the apparatus holding it be placed in a chamber, such as a large desiccator that can be evacuated. Start out with a dry porous plate and apply vacuum to the chamber by means of a vacuum pump or water aspirator for about 20 to 30 min. Then apply the deaerated wetting solution to the chamber in such a manner that the porous plate and the sample are wetted from the bottom, while maintaining the vacuum. A problem associated with vacuum wetting is the slaking of soil aggregates, which will result in a change in the water retention characteristics. Alternatively, the dry soil can first be flushed with CO_2 to replace the air present in the soil pores. The CO_2 will readily dissolve in the deaerated wetting solution during wetting of the soil, preventing the presence of trapped gas. It is good practice to flush the sample with several pore volumes of wetting solution to remove the CO_2 saturated solution, which may change the pH of the soil environment.

Independent of the wetting procedure used, it may be necessary to confine the soil sample to its original size by placing weights on top of the sample or by using a cap that cannot move. This is mainly necessary if the sample contains swelling clay minerals, which may cause expansion of the sample and therefore change the pore-size distribution and the porosity of the soil, and consequently the water retention curve.

3.3.2.1.f Temperature Effects

The intensity of the forces retaining the water in the soil at a given matric head is temperature dependent. The surface tension of the soil water decreases with increasing temperature, which leads to a reduction of water content at a given matric

head (Philip & de Vries, 1957; Haridasan & Jensen, 1972; Hopmans & Dane, 1986). The effects of temperature on the adsorptive forces are somewhat obscure, but again it appears that an increase in temperature leads to a reduction of the water content at a given matric head. Philip and de Vries (1957) were among the first to quantitatively describe the changes in a soil water retention curve due to temperature changes by considering the temperature dependence of the surface tension at the air–water interface. Although the temperature effect is intuitively clear, most experimental results do not match the predicted values based on the Philip and de Vries theory. Liu and Dane (1993) proposed a new theory that considers soil water to be composed of continuous water and isolated pockets of water. Measured soil water matric head values are assumed to be determined by the properties of continuous water only. They hypothesized that, when the temperature increases, water flows from these isolated pockets to the continuous phase, thus resulting in an additional temperature effect on the water retention curve. An equation based on this hypothesis yielded good agreement between predicted and experimentally determined temperature effects. The reversibility of temperature effects needs further investigation because a decrease in temperature may not cause the same increase in water content as the decrease caused by an increase in temperature.

Fluctuations of temperature tend to cause distillation of water from the wetted samples and the porous plate to the walls of the chamber enclosing the samples and plate. If volume outflow is being monitored, as is often the case, this process will interfere with the determination of the water content values of the soil sample. Temperature fluctuations should, therefore, be avoided as much as possible.

3.3.2.2 Hanging Water Column

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3.3.2.2.a Principles

The hanging water column technique to determine a water retention curve is performed in a Buchner funnel, also referred to as a *Haines apparatus*. In this apparatus (Haines, 1930), the wet sample is in hydraulic contact with the bulk water through a porous plate (see Fig. 3.3.2–3 for a simplified diagram). The gas pressure in the soil sample is at atmospheric pressure (P_{atm} , Pa), whereas the pressure in the bulk water is reduced to subatmospheric levels, either by reducing the level z_1 or by decreasing the controlled gas pressure P_g (Pa). The subsequent reduction in hydraulic head causes the water to flow from the soil sample. At static equilibrium, the water pressure head, h (m), decreases linearly with elevation according to

$$h(z) = -z + z_1 + (P_g - P_{\text{atm}})/\rho_w g \quad [3.3.2-2]$$

where z (m) is elevation (positive if above $z = 0$ and negative if below $z = 0$), z_1 (m) is the distance from the water level to the reference level for the gravitational head (we selected $z = 0$ at the point of contact between the soil sample and the porous plate), ρ_w (kg m^{-3}) is the density of the water, and g (N kg^{-1}) is the gravitational

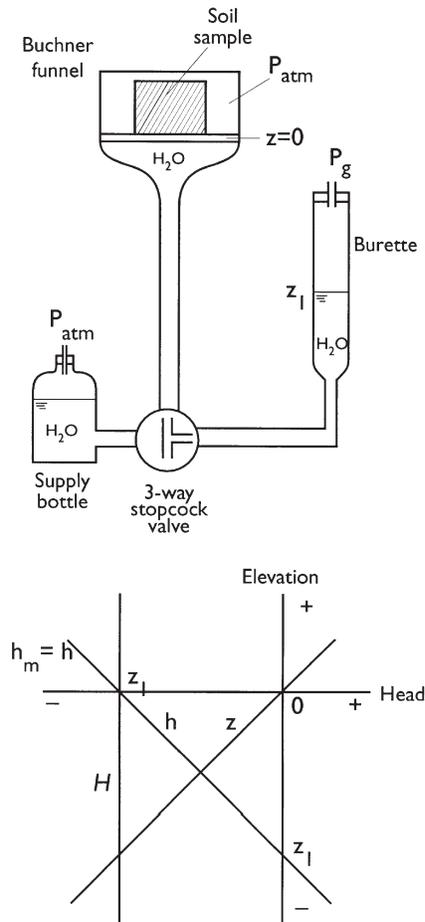


Fig. 3.3.2-3. Diagram of hanging water column method.

field strength. The distance z_1 is to be taken negative if z_1 is below $z = 0$ and positive if above. P_g may vary from values slightly greater than P_{atm} to values considerably smaller. It may be easiest to start with $z_1 = 0$ and then to first step-wise decrease h by decreasing z_1 followed by step-wise reductions of P_g . Water flows out of the sample until static equilibrium is reached. Outflow volumes and pressures in the bulk water are measured at each step to allow calculations of θ and the corresponding h_m values. If the air pressure in the sample is maintained at atmospheric pressure, $h_m = h$. Consequently, h_m varies linearly with elevation in the same manner as h . If the height of the soil sample is sufficiently small (e.g., 1 or 2 cm), the variation in h_m from the top to the bottom of the sample may be neglected. For those cases in which the change in h_m , and therefore in θ , should not be ignored, such as for coarser-textured and taller samples, a correction procedure is given in Section 3.3.2.10.

The absolute pressure in the bulk water cannot be reduced below its vapor pressure ($P_{\text{vap}} = 2.34$ kPa at 20°C) at the ambient temperature, as it would spontaneously vaporize (boil). Consequently, the theoretical lowest pressure head, h_{min} , that can be established in the suction apparatus is given by

$$h_{\text{min}} = (P_{\text{vap}} - P_{\text{atm}})/(\rho_{\text{w}}g) \quad [3.3.2-3]$$

In practice, because of dissolution of gases from the bulk water, the suction apparatus is limited to an h_{min} value of about -8.5 m (or -85 kPa) at elevations near sea level. The suction range is even more reduced at higher elevations because of the decrease of P_{atm} with elevation. An equilibrium head distribution is shown in Fig. 3.3.2-3.

3.3.2.2.b Equipment and Supplies

Buchner funnels can be purchased from scientific supply stores. It should be noted that the porous plates are specified by their largest pore size, which determines their air entry value. This is the value at which the pores in the plate can no longer hold the water due to the applied suction and the apparatus becomes unsuitable for further measurements. To detect the presence of air, it is best to connect the Buchner funnel to a supply bottle and a burette by means of clear tubing that will not collapse under the suctions applied to the water (Fig. 3.3.2-3). A three-way stopcock valve allows one to fill the tubing and to initially saturate the sample with the solution provided by the supply bottle. Subsequently, the stopcock assembly allows the measurement of outflow volumes during drainage of the sample or inflow volumes during imbibition. To control P_{g} , compressed air and air at subatmospheric pressure are needed in addition to pressure and vacuum regulators. The compressed air can either be supplied by an in-house air compressor or by air tanks available from a bottled gas company. An air filter should be used in the line between the air supply system and the pressure regulator that reduces the compressed air to a pressure compatible with specifications of any subsequent regulators. To regulate the pressure or vacuum applied to the burette, a subatmospheric pressure regulator is required (contact, e.g., Moore Products Co., Spring House, PA 19477 for an appropriate model). This regulator requires a vacuum in addition to a positive pressure source. The former can be provided by a vacuum pump. A water and mercury manometer, or other pressure measuring device such as a pressure transducer, should be connected to the pressure/vacuum regulator for precise measurement of P_{g} .

3.3.2.2.c Procedure

1. Fill the supply bottle, the tubing connected to the Buchner funnel, the tubing connected to the burette, and the space below the porous plate in the Buchner funnel with the solution to be used. It may be necessary to hold the funnel upside down briefly to remove air from below the plate.

2. Place the sample on the plate and raise the supply bottle enough to wet the sample. Water will also be standing on the plate outside the ring sample. Cover the Buchner funnel to prevent evaporation from the sample and the porous plate, but make sure that the soil air remains at atmospheric pressure.
3. Upon saturation of the sample, close the valve to the supply bottle and open the valve to the burette. Initially the burette should be raised to a level that will allow z_1 to be at the same level as the level of contact between the soil and the porous plate ($z = 0$). The air pressure applied to the burette should be atmospheric at this point. Adjust the burette until all outflow has stopped and $z_1 = 0$. This will be the starting point for the measurements. Record the burette reading.
4. Step-wise reduce the level z_1 , each time waiting until the outflow has stopped. Record the burette reading to allow calculation of the outflow water volume and measure z_1 . Once it becomes impractical to adjust the burette ($z_1 < -2$ to -3 m), reduce the controlled air pressure, P_g .
5. Upon reaching the desired matric head value, remove the sample from the plate. Weigh and oven-dry the soil at 105°C for approximately 48 h to determine the final volumetric water content from

$$\theta = (M_{ws} - M_{ods})/\rho_w V_s \quad [3.3.2-4]$$

where M_{ws} is the mass of the moist soil, M_{ods} is the mass of the oven-dry soil, ρ_w is the density of water, and V_s is the volume of soil (volume of ring sample).

6. From the consecutive outflow volumes determine the volumetric water content for each h_m value to obtain the water retention curve. Plot θ vs. h_m .
7. If a wetting curve is desired as well, step-wise increase P_g and/or the level z_1 after Step 4 of the procedure. Then continue as outlined.

3.3.2.2.d Comments

The hanging water column method is probably the easiest method to determine water retention curves, especially for $h_m > -2$ m, and no external vacuum source and pressure regulators are needed. Another advantage of the hanging water column method is that the air pressure in the soil sample is always at atmospheric pressure and has, therefore, no effect on the shape of the air–water interface because of the presence of trapped air as it has with the pressure cell method (Section 3.3.2.3.d). A limitation of the Buchner funnel is that only one sample can be analyzed at a time, unless more funnels are set up. This limitation is avoided by the use of a suction table (Section 3.3.2.6), which is based on the same principle.

One should also be aware that evaporation of water can occur through the tubing. If the measurements are critical, as for basic research, an additional hanging water column should be set up without a soil sample to measure the evaporation through the tubing, so that corrections can be made during the calculations of the water retention curves. Since each calculated water content value is an average value for each sample as a whole and is assumed to correspond to one matric pressure head value, which changes with elevation, it may be necessary to correct for this averaging as well. The correction procedure is outlined under Section 3.3.2.10.

3.3.2.3 Pressure Cell

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3.3.2.3.a Principles

In a pressure cell, the body of water under the porous plate is kept at about atmospheric pressure, while a gas phase pressure, P_a (Pa) > atmospheric pressure, is applied to the soil sample. Consequently, no water in the system is subjected to pressures greatly less than atmospheric (Fig. 3.3.2–4).

The analysis of static hydraulic equilibrium, when the ambient gas phase pressure on the soil sample is not atmospheric, requires recognition of a pneumatic component of the pressure head, h_a (m), which is given by $(P_a - P_{atm})/(\rho_w g)$. Therefore, when P_a is not atmospheric, the total pressure head, h , is given by

$$h = h_a + h_m \quad [3.3.2-5]$$

Although water flow occurs in response to gradients of h plus the gravitational head, z (i.e., $H = h + z$), where H is referred to as the *hydraulic head*, it is h_m that controls the water content of the soil sample.

When a wet soil sample is in contact with the wetted porous plate in a pressure cell and the gas phase in the cell is raised above atmospheric, water flows out of the sample through the porous plate due to the driving force caused by the increase in h_a . As the soil drains, h_m and H decrease. Eventually, static equilibrium is established between the soil water and the bulk water in the system below the porous plate. The static equilibrium distribution is shown in Fig. 3.3.2–4.

At static equilibrium, the matric head of the soil water, which changes linearly with elevation, in a similar manner as with the hanging water column method, is given by

$$h_m(z) = -[(P_a - P_{atm})/(\rho_w g)] + z_1 - z = -h_a + z_1 - z \quad [3.3.2-6]$$

where $(P_a - P_{atm})$ is the cell air-gauge pressure (positive), z_1 is the elevation of the water in the burette with respect to the gravitational head reference level ($z = 0$). Convenient levels for $z = 0$ are the contact level between the soil sample and the porous plate (Fig. 3.3.2–4), the top of structure on which the pressure cell is resting, or the counter top. If z_1 is below $z = 0$, it is negative; if it is above, it is positive. In most applications, h_m for the sample as a whole is calculated from the above equation by ignoring z_1 and z . As was shown by Liu and Dane (1995a, b), errors can be minimized by determining the h_m values at a height equal to the midpoint of the soil sample height. If the porous medium sample consists of a rather coarse material, large changes in water content may occur over the height of the sample if the sample height is greater than 1 or 2 cm. Corrections should then be applied as outlined in Section 3.3.2.10.

3.3.2.3.b Equipment and Supplies

Several companies (e.g., Soilmoisture Equipment Corp., P.O. Box 30025, Santa Barbara, CA 93105, <http://www.soilmoisture.com>; Soil Measurement Sys-

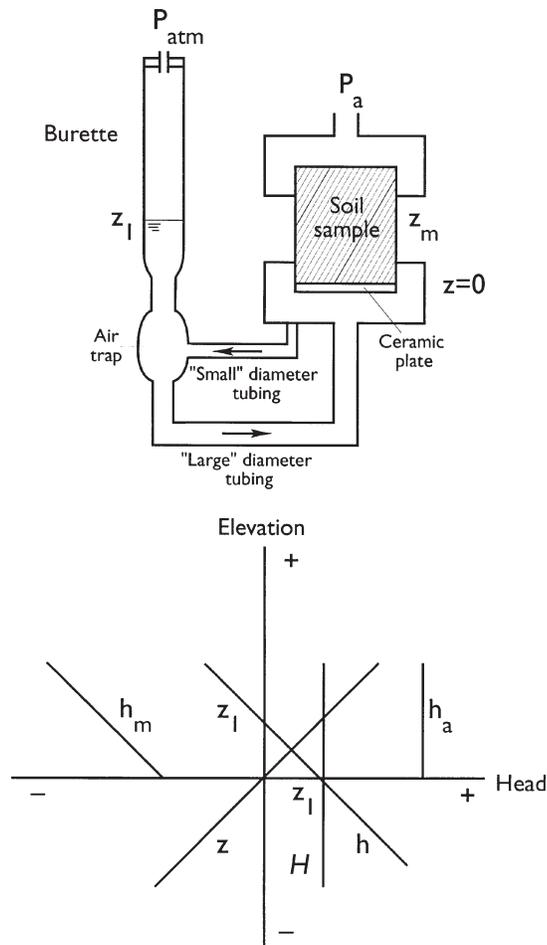


Fig. 3.3.2-4. Diagram of pressure cell method. The arrows indicate the direction in which the water should be circulated to remove air from the cavity below the porous plate.

tems, 7090 North Oracle Road, Tucson, AZ 85704, <http://home.earthlink.net/~soilmeasure/>) manufacture pressure cells in various sizes with porous plates consisting of different materials and having different air entry or bubbling pressure values. If none of their standard sizes fits your needs, for example, due to the diameter of the ring samples, special orders may be filled upon request. Another source for the manufacturing of pressure cells may be your local machine shop. If used for the determination of water retention curves, most pressure cells are constructed from clear plastic. The cells contain O-rings that hold the sample rings in place and prevent leakage of air and water. The top of a pressure cell needs to be connected to an air pressure source in the form of an in-house air compressor or an air tank available from a bottled gas company. Two pressure regulators are needed to provide accurate control of the applied air pressure. An air filter should be placed be-

tween the air supply source and a nonbleeding type, coarse regulator. This regulator reduces the air pressure to a level required for the input into a fine regulator (contact, e.g., Moore Products Co., Spring House, PA 19477 for an appropriate model). Most pressure cells, and their porous plates, are constructed to hold pressures not greater than 100 kPa. The fine regulator should be connected to a water and a mercury manometer, or an alternative pressure measuring device, to allow accurate measurements of all applied air pressures. An alternative to the use of compressed air is the use of bottled nitrogen. Nitrogen has the advantage that it is less soluble in water than oxygen and may therefore cause fewer problems with gas diffusion through and accumulation of gas below the porous plate.

The commercially available pressure cells usually have only one outlet at the bottom, which in many cases is used to let the water drain directly from the pressure cell. Outflow volumes are then determined from the water collected in a glass beaker. This procedure seriously compromises the determination of the water retention curve because of evaporation of water from both the pressure cell outlet and the glass beaker, and because of unknown amounts of air (gas) accumulation below the plate. The latter occurs as a result of air diffusion through the porous plate. A simple modification, such as the water circulation system depicted in Fig. 3.3.2–4, can be used to avoid these problems. First, install a second, but smaller diameter, outlet in the bottom cap inside the perimeter of the built-in cavity below the porous plate. Connect sections of Tygon tubing of appropriate diameters and lengths to the two outlets of the bottom cap and to an air trap, which in turn is connected to a burette. The larger size tubing should be resting on the counter top so it can be rolled and water can be circulated from the large size tubing into the bottom cap, then into the small size tubing, and finally into the air trap. As such, air (gas) bubbles trapped below the porous plate will be removed. Subsequent squeezing of the large size tubing will remove all air (gas) from the air trap, when it moves into the burette and into the atmosphere. The top of the burette should be covered to prevent evaporation, but a small hole must be provided to maintain atmospheric pressure in the air inside the burette.

3.3.2.3.c Procedure

1. Saturate the porous plate under vacuum. Place the appropriate O-ring in the bottom of the bottom cap, and place the saturated porous plate on top of the O-ring.
2. Place the appropriate O-ring in the side groove of the bottom cap and carefully put the ring sample into the bottom cap. It is helpful to have the O-ring coated with a thin film of stopcock grease, but make sure that the soil will not come into contact with the stopcock grease as it will affect the surface tension of the soil water. Alternatively, greases are now available which have a minimal effect on surface tension. It is also important that the O-rings remain free from soil particles to prevent leakage of air and/or water from the pressure cell.
3. Place the appropriate O-ring, coated with a thin film of stopcock grease, into the side groove of the top cap, and place the top cap on top of the ring sample.
4. Connect the top and bottom cap with the provided threaded rods and fasten the wing nuts hand tight. Do not overly tighten the wing nuts as the porous plate may crack.

5. Add water through the burette and squeeze the large size tubing if necessary so the water will start to fill up the air trap and the tubing. Roll the large size tubing with a small hand roller in the direction that will make the water flow into the cavity below the porous plate and into the small size tubing. Repeat this procedure until all air has been removed.
6. Satiating the soil sample by letting the water flow from the burette into the soil sample. At this point the water level in the burette should be above the top of the pressure cell. Once water starts to flow from the top of the cell, reduce the water level in the burette to slightly below the middle of the ring sample by either lowering the burette or removing water. If needed, connect the burette to a water supply bottle by means of a three-way stopcock valve, placed between the burette and the air trap, so that water can easily be drained from or added to the burette (as in Fig. 3.3.2–3).
7. Select a reference level for $z = 0$ and measure the distance to the level in the burette (z_1). Although not necessary, it is best to determine h_m at $z = z_m$, the distance from the reference level to the middle of the ring sample height. Knowing h_a , z_1 , and z , we can calculate h_m from Eq. [3.3.2–6]. It should be emphasized that the location at which h_m is calculated should remain the same for a given sample.
8. Increase h_a step-wise, each time waiting until the outflow has stopped, measure z_1 , and record the burette reading to determine the outflow volume between consecutive air pressure increases. It is good practice to calculate the value of h_m for each static equilibrium situation by substituting the values for z , z_1 , and h_a into Eq. [3.3.2–6] to keep track of the range of h_m values being used.
9. Once the most negative desired value for h_m has been reached, the ring sample should be removed from the pressure cell to determine the final volumetric water content. It is important to remove the soil sample from the pressure cell without allowing its water content to change, for example, due to back flow of water from the burette. To avoid this, continue to apply the last air pressure and remove all bulk water present in the system below the porous plate. Only then reduce the air pressure to atmospheric and quickly remove the ring sample from the pressure cell. Alternatively, the process of increasing h_a step-wise can be reversed; that is, h_a is step-wise decreased to obtain an imbibition curve.
10. Take a weight measurement of the moist soil and dry it in the oven for approximately 48 h at 105°C to determine the final volumetric water from Eq. [3.3.2–4].
11. Calculate all other volumetric water content values based on the outflow volumes measured in the burette and match these values with the corresponding h_m values to yield a set of the water retention points that can be used to obtain the water retention curve by fitting a parametric model to the retention data (Section 3.3.4).

3.3.2.3.d Comments

As long as a soil sample in a pressure cell apparatus is at static equilibrium, $h_a > 0$ and $h_m < 0$. When the gas pressure is released and the soil sample is removed from the porous plate, it is usually assumed that the value for h_m remains unchanged. However, this assumption may not be valid if isolated bodies of entrapped air exist

within the aqueous phase of the sample. These entrapped air pockets will tend to expand when the reduction of the gas phase is transferred to the liquid phase. The expansion of the entrapped air will affect the curvature of the interface between the solution phase and the continuous gas phase, and hence affect the value of h_m . As was shown by Chahal and Yong (1965) and De Backer and Klute (1967), the value for h_m usually increases upon release of the gas phase pressure. This change is largest near saturation.

It is quite common to observe an increase in water content during the first applied value(s) of h_a . The compression of entrapped air pockets causes water to flow from the body of free water below the porous plate into the soil sample. This increase in water content is an artifact and should be ignored in the calculations. One should also be aware that evaporation of water can occur through the tubing. If the measurements are critical, as for basic research, a companion pressure cell should be set up without a soil sample to measure the evaporation through the tubing. Corrections can then be made during the calculations of the water retention curves of the actual soil samples. Since each calculated water content value is an average value for each sample as a whole, corresponding to one matric pressure head value, it may be necessary to correct for this averaging as well. The correction procedure is outlined in Section 3.3.2.10.

For remarks about unintended changes in the applied air pressures while waiting for static equilibrium, the reader is referred to Section 3.3.2.4.d.

3.3.2.4 Pressure Plate Extractor

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3.3.2.4.a Principles

Both the hanging water column and the pressure cell method are limited to a minimum h_m value of about -8.5 m. The use of a pressure plate extractor avoids this limitation because it is built to withstand high pressures. The principles are similar to those discussed for the pressure cell. Since we are now dealing with much higher pressures, and hence more negative values for h_m , we can assume that the change in h_m with elevation within the soil sample is negligible compared with the value of h_m itself. The values can therefore be calculated from

$$h_m = -(P_a - P_{atm})/(\rho_w g) = -h_a \quad [3.3.2-7]$$

3.3.2.4.b Equipment and Supplies

Depending on the desired values of h_m , pressure plate extractors can be purchased that withstand pressures up to 500 (5 bar) or 1500 kPa (15 bar) (Soilmoisture Equipment Corp., P.O. Box 30025, Santa Barbara, CA 93105). Pressure plate extractors are substantially bigger than pressure cells. They can usually hold several porous plates. Each plate has a screen, to expedite lateral movement of water, and a rubber sheet covering the bottom. The rubber sheet is mounted to the edge

of the plate. An outlet from the space between the plate and the backing sheet leads through the ceramic. This outlet is connected by a short piece of pressure tubing to an outlet in the pressure chamber. This outlet is in turn connected to a glass beaker or a burette slightly filled with water to detect air leaks. Water present between the plate and the rubber backing sheet is therefore near atmospheric pressure, independent of the air pressure applied to the soil samples present in the chamber. Each plate can hold from five to eight soil samples. Plates are available with different bubbling pressures. Because the conductance of a plate decreases with increasing bubbling pressure, it is important to match the porous plate with the range of desired h_m values.

In addition to the pressure chamber(s) and porous plates, an air pressure supply and pressure regulation system is required. An in-house air compressor, or bottled air or nitrogen, can be used as the pressure supply source. An air filter should be placed in the line between the compressed air (gas) and a nonbleeding type regulator to provide the specified pressure to a second regulator to be used in conjunction with the pressure chamber. Because of the relatively high pressures involved a pressure gauge should be used rather than a water and/or mercury manometer (all components are available from Soilmoisture Equipment Corp., Santa Barbara, CA 93105).

3.3.2.4.c Procedure

The outlined procedure applies to both the 500- and the 1500-kPa pressure plate extractor apparatus, or to any similar pressure extraction system.

1. Make sure all pressure lines, filter, pressure regulators, and gauges are properly connected.
2. Take a porous plate with the desired bubbling pressure and saturate it with deaerated water (0.005 M CaSO_4 solution) by connecting the outlet to a water source and filling the space between the rubber backing sheet and the porous plate. At some point during the filling process, disconnect the supply tubing and remove the air from the space between the plate and the rubber sheet. Terminate the filling process once the rubber backing sheet is extended about 2 cm. Let the plate sit until considerable sweating of the ceramic plate is observed.
3. Drain most of the water from the space between the plate and the rubber sheet and place the plate in the pressure chamber. Connect the pressure tubing to the plate at one end and to the inside end of the pressure chamber outlet at the other end. Make sure that the tubing on the outside end of the pressure chamber outlet is connected to a burette or submerged under water in a glass beaker.
4. Place the soil samples, either disturbed or undisturbed, on top of the porous plate. The soil should be contained in rings, preferably no higher than 1 cm. Add 0.005 M CaSO_4 solution to the plate and/or the soil samples until the soil samples are satiated.
5. Close the pressure chamber and apply the desired air pressure. Water will start to flow out of the pressure chamber, as can be observed from the water level in the burette or glass beaker. Excessive air bubbling from the outflow tubing is an indication of a leak in the porous plate. Measurements should be abandoned and restarted with another porous plate.

6. Once outflow has ceased, disconnect the outflow tubing from the pressure chamber, reduce the applied pressure to atmospheric, open the pressure chamber, and quickly remove and weigh the moist samples (M_{ws}).
7. If water content values are needed at additional values for h_m , return the samples to the porous plate and repeat Steps 4 through 6. If no more measurements are needed, transfer the soil samples to tin cans and dry in the oven for approximately 48 h at 105°C to obtain the mass of the oven-dry samples (M_{ods}).
8. Calculate the volumetric water content corresponding to each value of h_m according to Eq. [3.3.2–4]. If the volume of the soil is unknown, only the gravimetric water content (w) can be calculated according to

$$w = (M_{ws} - M_{ods})/M_{ods} \quad [3.3.2-8]$$

3.3.2.4.d Comments

In many cases, there will be some fluctuation of the regulated gas pressure during the equilibration time of the samples. If these fluctuations are small enough to be within the specified tolerances of the regulator, it is best not to readjust the regulator. If they exceed these tolerances, however, some action needs to be chosen to prevent the introduction of hysteresis. If drainage data are being collected and the applied pressure has decreased more than one would expect from the specified tolerances, it is appropriate to increase the regulated output pressure to its original value. If the applied pressure has increased, the regulator should not be readjusted to a lower cell pressure. If wetting retention data are being collected and an increase in the applied pressure is observed, the regulator should be adjusted to its original value. If the applied pressure has decreased, the regulator should not be adjusted. It should also be noted that at the higher applied pressures, that is, at the more negative values of h_m , complete equilibration within the sample may not be achieved.

3.3.2.5 Long Column

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3.3.2.5.a Principles

Unless computational corrections are applied, as outlined in Section 3.3.2.10, the standard procedures for the hanging water column and the pressure cell methods will yield average values of θ over the total sample, corresponding to values of h_m that apply to only one point along the sample height. The results may thus differ substantially from those that apply to a physical point, especially for coarser materials. These errors can be avoided, however, if measurements are obtained directly at physical points as outlined by Dane et al. (1992). In this method, water content values are determined at physical points along a 1-m-long column, either during drainage or imbibition, with a gamma radiation system (Section 7.2.2.1.a). The bottom of the column is connected to a supply–drainage bottle, the elevation of which is changed in a step-wise fashion. The corresponding values for h_m are determined from the known water pressure distribution at each static equilibrium situation, as-

suming that the air pressure is equal to atmospheric pressure at all locations. Because of the 1-m height of the column, water content values near the top will usually approach those of the residual water content if the porous medium is rather coarse. In principle, the procedure is equivalent to the one with the hanging water column depicted in Fig. 3.3.2–3. The water level in the bottle will, however, usually be above the bottom of the column, so that no porous plate is needed.

3.3.2.5.b Equipment and Supplies

A 1-m glass column with Teflon end caps is needed to hold the porous medium. Although other materials can be used, the choice of the aforementioned materials makes it possible to use the setup for liquids other than water, such as organic solvents. The bottom cap is connected to a supply–drainage bottle with flexible tubing long enough to allow the level of the water to be flush with the top or the bottom of the column. The top cap should be open across the inside cross-sectional area of the column to allow filling of the column and to allow for easy exchange between water and air. Filling the column can be accomplished as outlined in Section 3.3.2.1.c. The inside diameter of the column should be between 5 to 8 cm, and the thickness of the glass should be approximately 6 mm. A gamma radiation system is required to measure the water content values at discrete points along the column. A full description of the use and calibration of such a system is provided in Chapter 7. We recommend use of the single-source method (Oostrom et al., 1998). An alternative to the use of gamma radiation for water content measurements is the use of small time domain reflectometry probes (Section 3.1.3).

3.3.2.5.c Procedure

1. Determine all calibration constants (attenuation coefficients for water and soil, and path lengths and incident count rates for the discrete points along the column where measurements will be obtained) for use with a gamma radiation system (Section 7.2).
2. Pack the column. This can be done under water or with dry soil. In the latter case, the packing must be followed by flushing with CO₂ and saturation with water from the bottom (Section 3.3.2.1).
3. Displace the soil water with air by step-wise lowering of the supply–drainage bottle, each time waiting until outflow has stopped. It is advantageous at this point to work with a burette rather than a bottle to check for equilibrium. This burette should be connected to the tubing leading from the bottle to the column with a three-way stopcock valve. The operator then has a choice to use the burette or the supply–drainage bottle. This configuration also allows for the removal of water from or the addition of water to the burette.
4. Once static equilibrium has been attained, record the water level in the burette to determine the $h_m = h$ values in the soil water as a function of elevation and determine volumetric water content values with the gamma radiation system. Note that $h_m = h = 0$ at the water level in the burette and decreases linearly with increasing elevation.
5. Continue to reduce the water level until the desired range of h_m values is obtained.

6. For each discrete point, pair the volumetric water content and matric pressure head value to obtain a set of water retention points during drainage.
7. If imbibition data are needed, continue the experiment by increasing the water level step-wise and repeat Steps 3 through 6.

3.3.2.5.d Comments

Use of the long column method to determine water retention curves should be limited to rather coarse materials because no values for h_m less than -1 m can be obtained. The advantage is, however, that the obtained data apply to physical points, the size of which is determined by the size of the collimated beam of the gamma radiation. The limitation to coarse materials can be eliminated if a porous plate is used at the bottom of the column. This will allow the operator to reduce the water level, and/or reduce the air pressure in the burette and/or supply–drainage bottle to obtain smaller values of h_m .

3.3.2.6 Suction Table

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3.3.2.6.a Principles

The suction table allows drainage water retention characteristics to be determined from saturation to a minimum matric head of about -5.0 m. Water-saturated soil samples are placed on a porous barrier subjected to suctions, that is, negative pressures. The porous barrier consists of one or more layers of fine materials and the maximum allowable suction depends on the air-entry characteristics of the materials placed in the suction table apparatus. A series of static equilibria is established between the water in the soil samples and a free body of water contained in a suction control system at known potential. At each equilibrium level, the volumetric soil water content, θ , and the related matric head, h_m , are determined. These pairs of measured θ and h_m values represent data points of the soil water retention curve.

Although the suction table method has been used for many years (Jamison & Reed, 1949; Jamison, 1958; Clement, 1966), its popularity increased after the publication of the paper by Stakman et al. (1969). These authors proposed the use of a very fine sand, or a layered material made up of sand and kaolin, as the porous medium for the suction table. If filled only with sand, the suction table is suitable for measurements in the suction range of 0.15 to 1.0 m. The higher air-entry value of a sand–kaolin porous bed allows the determination of soil water retention data to a suction of about 5.0 m. Some versions of suction tables are commercially available (Van Walt Ltd., Prestwick Lane, Grayswood/Haslemere, Surrey GU27 2DU, United Kingdom). As undisturbed soil samples are generally collected in brass or stainless steel cylinders with heights of 0.03 to 0.05 m and outside diameters of 0.05 to 0.08 m, a suction table can typically hold 20 to 40 soil samples. Varallyay (1973)

described the design of a transparent plastic container with an efficient, although rather elaborate, drainage system to remove air bubbles from a vacuum chamber filled with water. For suctions up to 2.0 m, Ball and Hunter (1988) suggested using a porous barrier consisting of a glass microfiber membrane covered with a 1.0-cm-thick layer of silica flour.

3.3.2.6.b Equipment and Supplies

Although useful and detailed information on how to construct a suction table can be found in Stakman et al. (1969), we will present the description of a recently designed suction table which is capable of reaching suction values up to 4.0 m (Comegna et al., 1994; Fig. 3.3.2-5 and 3.3.2-6). The material used to build the container is Perspex, which has the advantages of being transparent, relatively cheap, and easily machinable. It is also light and shock resistant, so that transportation should not be a problem. The container is covered with a Perspex lid to prevent evaporation. A rubber gasket is situated at the edge of the container walls to improve sealing of the lid. If the suction table is not placed in an environmentally controlled room, evaporation and condensation may occur, which affects the water content of the soil samples. An alternative to a constant temperature room is the use of low-resistant heaters attached to the lid with epoxy glue. All of the connections between the various parts that constitute the suction table consist of flexible plastic tubing (e.g., Tygon tubing).

A channel system at the base of the Perspex container (Fig. 3.3.2-5) allows for easy water drainage and the removal of air trapped in the channels, which run parallel to the length of the container. Comegna et al. (1994) engraved the channels using a laser beam. The length and number of channels depend on the dimensions of the container. Issues concerning the overall dimensions of a suction table will be discussed below. The drainage channels, however, should be kept at least a few centimeters from the walls to maintain rigidity of the apparatus and good contact between the porous bed and the base of the container. Two transverse channels are drilled at a slightly lower elevation, one for inflow and one for outflow purposes, and are connected to the ends of the drainage channels. The inlet channel is connected to a small flask with a Pyrex, two-way stopcock valve, whereas the outlet channel provides the connection between the porous material and the suction control systems via a three-way stopcock valve. The small flask supplies water to allow removal of air bubbles from the drainage channels by flushing water from the inlet to the outlet channel.

The porous material used to equilibrate the water in the soil samples with an external body of water at the desired suctions is comprised of a glass microfiber membrane of fine porosity overlain by a layer of silt-kaolin mixture. Glass microfiber sheets are commercially available from factories that produce filter media and membranes (e.g., Pall Gelman Laboratory, 600 South Wagner Rd., Ann Arbor, MI 48103-9019, USA; Whatman Inc., 100 Ames Pond Drive, Tewksbury, MA 01876-0962, USA). The sheet should not be cut to fit the dimensions of the container. Rather, the dimensions of the suction table should be adjusted to fit those of the selected glass microfiber sheet. The silt-kaolin mixture is made up of a loose mixture of 50% silt, with a particle-size distribution in the 10- to 50- μm range, and

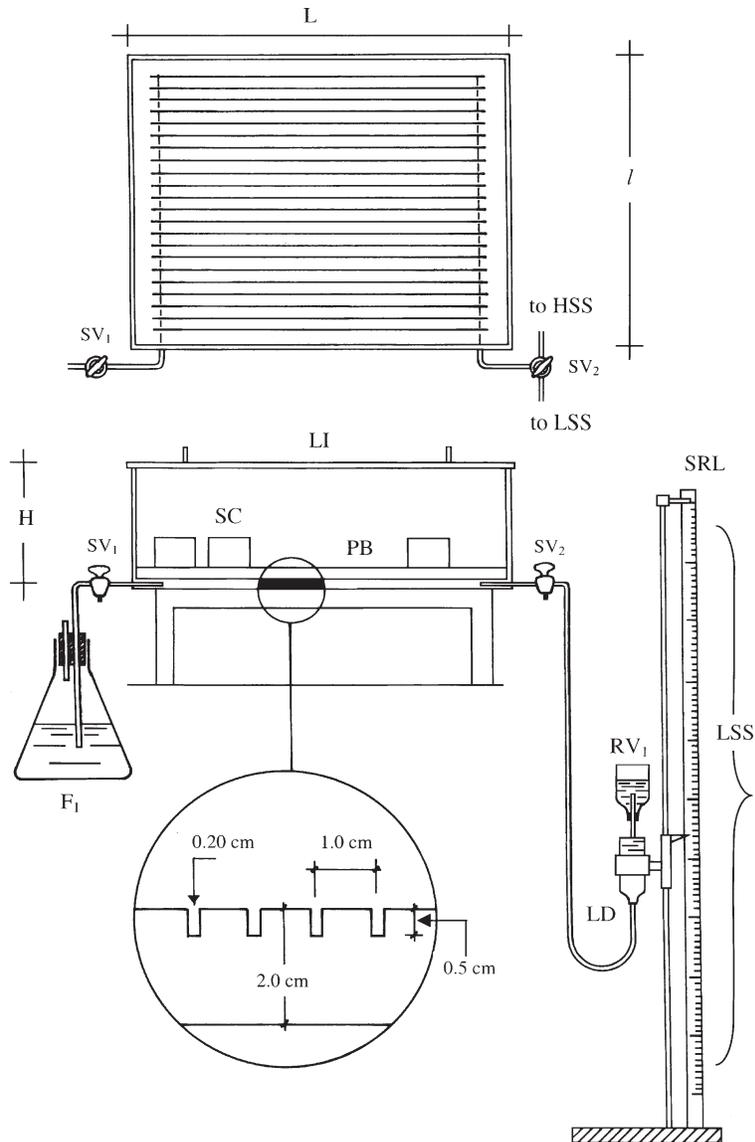


Fig. 3.3.2-5. Schematic diagram depicting the various components of the suction table apparatus (figure is not drawn to scale). The top view shows the inflow-outflow channels (dashed lines) underlying the drainage channels (solid lines). The flask F_1 supplies water to the suction table via the two-way stopcock valve SV_1 . The three-way stopcock valve SV_2 allows for outflow of water through the high suction system, HSS (bubble towers + vacuum pump system), or the low suction system, LSS (hanging water column system). A small supply reservoir RV_1 is placed on top of the leveling device to maintain a constant water level at the elevation of the overflow tube, which may otherwise change due to evaporation losses. LD is a leveling device with an overflow tube to drain excess water; LI is a lid with a lifting handle; PB denotes the porous bed; SC refers to soil core; and SRL is a stainless-steel ruler.

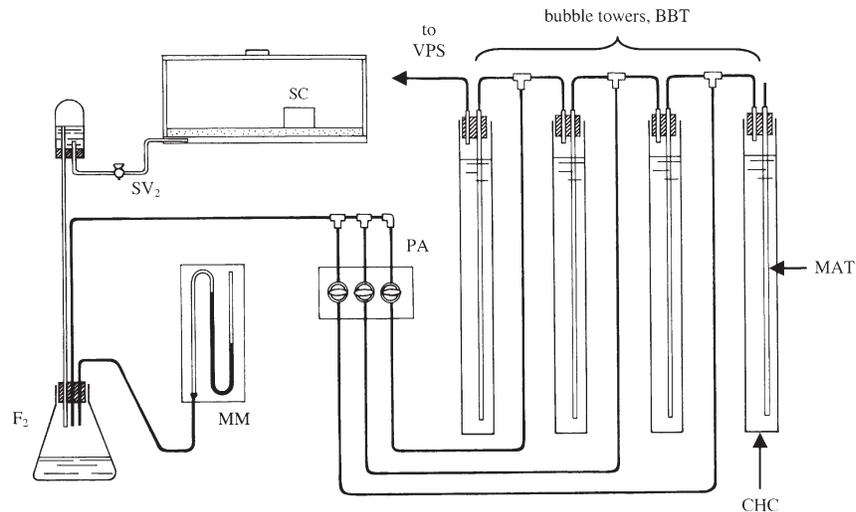


Fig. 3.3.2-6. Schematic diagram of the suction table apparatus connected to the high suction system (HSS) (figure not drawn to scale). The flask F_2 links the suction table to the bubble towers (BBT) and is also connected to a mercury manometer, MM, to obtain suction measurements. The vacuum pump system, VPS, is not shown in the figure. A needle valve is inserted into the line connecting the BBT with the VPS to allow fine regulation of the applied suction. CHC denotes constant-head cylinder; MAT refers to Mariotte tube; PA is a panel with stopcock valves; SC is soil core; and SV_2 is a three-way stopcock valve, which allows for the outflow of water by means of the HSS or LSS (see Fig. 3.3.2-5).

50% kaolin clay, having particles $<2 \mu\text{m}$ in diameter. To install the porous sheet, the container is first filled with approximately 1 cm of deaerated water by opening the two-way stopcock valve connected to the small flask and the inlet channel. Upon closing the valve, the glass microfiber sheet is placed on the water surface. Water is then removed by opening the three-way stopcock valve connected to the outflow channel on one end and a hanging water column (Tygon tubing connected to a supply-drainage bottle with overflow) on the other end. By increasing the length of the hanging water column, such that the level of water in the container drops very slowly, the sheet settles and adheres to the bottom of the container due to the tension in the water. Next, the three-way stopcock valve is closed and an aqueous suspension of the silt-kaolin mixture is poured slowly and evenly across the entire sheet until it is covered by a 1.5-cm-thick layer. After water evaporates and the porous layer becomes denser, the surface should be accurately leveled.

The Perspex container depicted in Fig. 3.3.2-5 has a length of 57.5 cm, a width of 46.5 cm, and a height of 20.0 cm, while the walls have a thickness of 0.63 cm. The base has a thickness of 2.0 cm to provide mechanical strength and rigidity. This is useful for transportation purposes and allows for engraving of the drainage channel system and drilling of the inlet and outlet channels. The drainage channel system consists of 43 channels placed 1.0 cm apart, each having a length of 52.0 cm and a depth of 0.5 cm. If sample cylinders of 7.0 cm in diameter are used, this suction table can hold 24 soil samples spaced sufficiently far apart to accommodate their placement and removal. Figure 3.3.2-5 includes the hanging water column sys-

tem, which is used to regulate the suction in the range from 0 to about 1.0 m by sliding a constant-level bottle with overflow tube along a rod. A ruler with centimeter graduation is used to locate the position of the overflow tube. The origin of the vertical axis is conventionally set at one-half the height of the soil sample so that the elevation of this point represents the datum.

Figure 3.3.2–6 shows an overview of the entire experimental facility with specific reference to the devices for controlling the applied suctions in the range from 1.0 to about 4.0 m. A constant-head cylinder system now controls the applied suction. This device is comprised of a number of Mariotte clear plastic or glass cylinders placed in series to form bubble towers. Each cylinder is about 5.0 cm in diameter and has a two-hole rubber stopper at the top. A bubble tube, about 2 to 3 mm inside diameter, is inserted in one hole of the rubber stopper, whereas the other hole is used to receive a short glass tube for the connection to the adjacent cylinder via plastic tubing and a T-shaped connector. One end of each T-shaped connector is linked to a two-way glass stopcock valve placed on a panel. These stopcock valves control the sequential operation of the constant-head cylinders. The lower end of each cylinder also has a rubber stopper. Inserted needle valves should be adjusted so that the bubbling rates are approximately two to three bubbles per minute. Depending on the length of the bubble tubes and the number of the cylinders in use, different constant water suctions can be obtained up to approximately 4.0 m.

3.3.2.6.c Procedure

First, the soil samples, contained in cylinders either as undisturbed or packed samples, are saturated with a deaerated 0.005 *M* CaSO₄ solution. This can be achieved by wetting the samples gradually from the bottom using the following procedure (Ball & Hunter, 1988):

1. Place each soil sample on a cloth-covered, perforated Perspex disk and place in a basin. Add water to the basin and maintain a level of 0.5 cm with respect to the bottom of the cylinders for 48 h.
2. Slowly add water and maintain a level of 2.5 cm with respect to the bottom of the cylinders for 6 h.
3. Raise the level in the basin to submerge the samples. Maintain for 4 h.

The samples are then weighed to obtain the mass of the saturated samples and placed on the suction table by pressing them slightly to establish good hydraulic contact between the soil and the porous bed material. The lower end of the soil sample is covered by a voile held in place with an elastic band. Even if the suction table is placed in a constant temperature room and is provided with a lid to prevent evaporation, it is good practice to cover the upper end of each soil sample with a paraffin film disk. If needed, a tiny hole can be punctured into the disk to maintain atmospheric pressure in the soil air.

The determination of the water retention curves starts by imposing a very low suction. Up to about 1.0-m suction, the applied suction is the difference in elevation between the datum and the overflow tube of the leveling bottle. For greater suctions, step changes are applied with the bubble tower system. Once the suction is

set, sufficient time should be allowed for the soil water to reach hydrostatic equilibrium. This can be checked by weighing each soil sample once every 24 h or more. If two consecutive masses of a given sample do not differ by more than 0.1 g, hydrostatic equilibrium can be assumed. The weighing procedure is as follows:

1. Remove the soil sample from the porous bed, dry the cylinder, and weigh the sample plus cylinder using a precision balance.
2. Record the mass.
3. Spray the area where the sample will be replaced with the wetting solution.
4. Replace the soil sample in its original position by applying a slight pressure to reestablish hydraulic contact. Repeat the weighing process on a daily basis.

Equilibration times depend mainly on the soil texture, applied suction, and hydraulic contact between the soil sample and the porous bed. The time required to reach equilibrium may vary from 2 to 4 d for suctions <0.20 m to more than 25 d for suctions of 4.0 m (Topp & Zebchuk, 1979; Ball & Hunter, 1988; Comegna et al., 1994). However, equilibration time also depends on the height of the sample. Soil sample size should be chosen with respect to the structural characteristics of the soil under study. In general, good results have been obtained using soil samples with a height of 5.0 cm and a diameter of 7.0 cm. For coarser porous media, samples 3.0 cm in height and 5.0 cm in diameter can be used. Especially at higher suctions, equilibration times are larger for coarse-textured soils due to their low hydraulic conductivity values.

Once the sample masses have been recorded for the final suction level, the soil samples are placed in an oven and dried at 105°C for 24 to 48 h. Upon removal from the oven, the samples are transferred to a desiccator with an active desiccant, and weighed again after they have cooled to room temperature. The volumetric soil water content, θ , at the final suction is calculated from Eq. [3.3.2–4]. Water content values at all previously applied suctions are then calculated from the consecutive mass differences divided by the density of water.

3.3.2.6.d Comments

Suction tables must be serviced regularly, even during periods of inactivity. They should always be inspected for the presence of air bubbles, hence the use of a transparent container. Whether or not air bubbles are detected, we suggest flushing the drainage and in- and outflow channels at 3- to 4-d intervals with deaired water containing trace amounts of mercuric chloride and thymol to prevent bacterial growth. Even when the container is void of samples, the porous medium bed should be moistened periodically.

Suction tables provide a versatile and cost-effective method to determine the drying soil water retention characteristics, because of the relative low cost of the equipment, together with the easy setup and operation, and the possibility of analyzing a large number of soil samples at a time.

The efficiency of the method with respect to soil texture raises the question of equilibration time. Using a tensiometer, one can conveniently monitor the at-

tainment of the equilibrium condition within a soil sample. A dummy soil sample with a tensiometer embedded into the top can be used for this purpose. The information gained from this dummy sample, however, may not be representative of all samples if soil samples of different textures are placed into the container. Alternatively, a tensiometer with a disk of sintered glass as the porous membrane can be pressed on the upper surface of each soil sample and the related suction measured by a mercury–water manometer or pressure transducer. At equilibrium, the tensiometer measures the value of the matric head equal to the imposed suction plus one-half of the sample height. This procedure allows a suitable monitoring of hydrostatic equilibrium and can reduce significantly the number of repeated weighings of the samples. It does not, however, alleviate the problem of waiting until each soil sample has reached its own equilibrium condition. An operational solution to this issue is the use of a nomogram, which is based on the assumption that outflow data as a function of time at a constant suction follows an exponential-type relationship (Stol, 1965). It is important to note that the practical advantage of employing the nomogram approach occurs at the greatest suctions, as one does not wait for static equilibrium to occur before recording the sample weights.

Comegna et al. (1994) showed that the discrepancies between retention data obtained with suction tables and those obtained for the same soil in the field under transient conditions occurred mainly at low suctions and were the result of slightly different degrees of initial saturation. Ciollaro and Romano (1995) and Santini et al. (1995) found relatively small differences between retention curves obtained with suction tables and those obtained with transient laboratory evaporation experiments.

Apart from the fact that suction tables enable only the determination of drainage retention curves, the procedure has another limitation. Especially at greater suctions, repeated removal of the samples for weighing can cause the loss in hydraulic contact between the soil water in the sample and the water in the suction table, and hence lead to inaccurate results.

It is good practice to place soil samples having similar textures in the same container. This allows for approximately equal equilibration times of the samples. To more easily restore hydraulic contact between the porous bed and the samples, their locations should be marked so that they can be replaced in their original position after weighing.

3.3.2.7 Controlled Liquid Volume

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3.3.2.7.a Principles

With traditional water-retention techniques, such as the pressure plate or cell, fixed gauge pressures are applied to the soil–air–water system and water is allowed to drain out of the sample until equilibrium water contents are reached. A different approach to defining points on a retention curve involves extracting or adding water to a sample in fixed-volume increments and allowing the matric head, h_m , to equilibrate with time. In each step, a known volume of water is extracted (or added), leaving the sample with a known average water content. Water then redis-

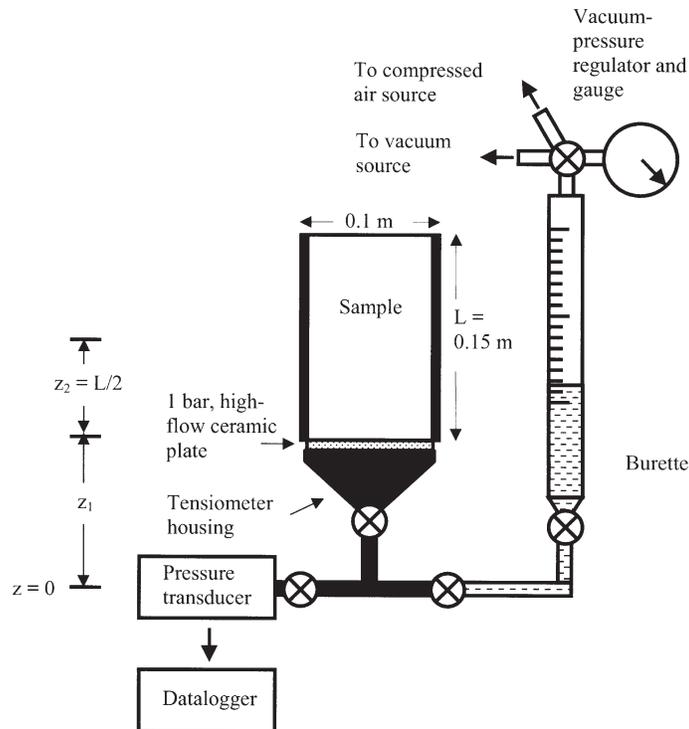


Fig. 3.3.2-7. Laboratory apparatus to rapidly measure water retention using the controlled-volume technique.

tributes within the sample until the pressure is equalized. Each measured equilibrium h_m is paired with the average volumetric water content to define points on the retention curve. With the “null” method described by Su and Brooks (1980), Dumbleton and West (1968), Leonard and Low (1962), Croney and Coleman (1954), and Miller (1951), the pressure imposed on the system is adjusted until it matches that of the soil water to determine h_m . A variation of the null method, described in the following subsections, uses a pressure transducer to monitor equilibration at a point within the sample (Fig. 3.3.2-7), while still holding the water content fixed for each point on the retention curve. The discussion hereafter will be directed toward the determination of drying curves, although the method should apply equally well for wetting curves.

3.3.2.7.b Equipment and Supplies

The basic components consist of a subatmospheric pressure regulator, a large-capacity (100–250 mL) graduated burette for measuring volume outflow, a membrane to transfer water between the sample and the burette and to serve as a tensiometer, and a system for recording the water pressure with time. Various tube fittings, ball valves, and polyethylene tubing are used to make the connections between components. Several types of membranes can be used for outflow, includ-

ing porous ceramic plates, thin filter membranes, or a fine-grained porous material (e.g., plaster, diatomaceous earth, or silt). For the arrangement shown in Fig. 3.3.2–7, a ceramic plate is coupled to a custom-made, stainless-steel housing and a pressure transducer. This allows its use as both a membrane for outflow and a tensiometer to determine pressure equilibrium. A ceramic plate should be chosen with a bubbling pressure higher than the anticipated range of water pressures to be measured during the experiment (e.g., 1 bar, high-flow, available from Soilmoisture Equipment Corp., Santa Barbara, CA 93105).¹ The pressure transducer should be chosen with a similar range of pressure (e.g., Honeywell Micro Switch pressure sensors, type 26PCC, 100-kPa differential range).

To control the volume of water exiting the sample, a subatmospheric vacuum-pressure regulator (model 44-20, range –95 kPa to 0 to 5 kPa gauge; Moore Products Co., Spring House, PA 19477) is attached with polyethylene tubing to the top end of the burette. The regulator must also be connected to laboratory air pressure and vacuum lines, preferably with an air filter inserted in the pressure line to ensure a clean source. The applied vacuum pressure in the burette is monitored using a vacuum-pressure gauge attached to the regulator. Other requirements include (i) a system for monitoring output voltage from the transducer, such as a data logger, computer data-acquisition system, or voltmeter; (ii) a means of applying an external force on the sample to provide a good hydraulic connection between the ceramic plate and the sample material; (iii) good laboratory temperature control (preferably within a range of 1–2°C); and (iv) a stable, vibration-free work area. For example, the device can be mounted on a system of steel bars, with the sample and burette in upright positions.

3.3.2.7.c Procedure

The procedure outlined here describes the method for attaining points on a drying curve. As an example of operating conditions that might be typical for a coarse-textured soil, Table 3.3.2–1 presents data for each extraction and equilibration step. Typical equilibration times are on the order of hours, as indicated in Table 3.3.2–1, and vary with the texture and size of the sample, the speed at which water is extracted, the regulator pressure, and the water content of the sample. A good seal is needed between the ceramic and the sample liner to prevent leakage (Fig. 3.3.2–7).

1. Calibrate the pressure transducer against known pressure heads (by using a water column, mercury manometer, or other means) to define the equation for converting output voltages from the transducer to pressures.
2. Saturate the sample and record the mass, M_{ws} , for later determination of θ_s , the saturated water content. The sample can be either vacuum saturated for complete saturation, or placed in a dish containing the wetting solution to allow imbibition of water from the bottom for saturation that may include some trapped air (Section 3.3.2.1.e). The time to saturate a sample usually varies from several hours to several days.

¹ The use of product or company names does not signify their endorsement by the U.S. Geological Survey.

Table 3.3.2-1. Example laboratory data sheet for water retention measurements using the controlled-volume method.

Sample length, L	0.147 m	Bulk sample volume, V_s	$1.017 \times 10^{-3} \text{ m}^3$			
Correction factor for h_m , $-(z_1 + z_2)$	0.201 m	Lab temperature	22°C			
Oven-dry weight, M_{ods}	1.913 kg	Saturated weight, M_{ws}	2.199 kg			
Density of water, ρ_w	997.8 kg m^{-3}	Saturated water content, θ_s	$0.2818 \text{ m}^3 \text{ m}^{-3}$			
Cumulative volume extracted $\Sigma\Delta V_w$	Cumulative reduction in water content $\Sigma\Delta\theta$	θ	h_m (Corrected to midpoint)	Vacuum-regulator pressure h_{ext}^\dagger	Time for extraction ‡	Time for equilibration §
mL	$\text{m}^3 \text{ m}^{-3}$		m		h	
0	0.0000	0.2818	0	0	--	--
5	0.0049	0.2769	0.29	0.4	0.20	0.42
13	0.0128	0.2691	0.47	0.6	0.88	4.58
33	0.0324	0.2494	0.54	0.9	3.88	18.05
61	0.0600	0.2219	0.83	1.2	4.80	17.42
87	0.0855	0.1963	1.40	1.6	25.45	13.5
110	0.1082	0.1737	1.86	2.2	6.78	12.42
134	0.1318	0.1501	2.51	2.8	8.05	9.62
154	0.1514	0.1304	3.18	3.2	24.83	13.67
173.5	0.1706	0.1112	3.99	4.2	25.25	15.33

† The height of water in the burette (not indicated here) affects the actual applied pressure, h_{ext} . The higher the water level is in the burette, the less effective the external pressure is in pulling water from the sample, which acts to decrease the difference $\delta h = h_{\text{ext}} - h_m$.

‡ Time for extraction depends on the amount of water being extracted and the difference between the vacuum-regulator pressure and the matric pressure of the sample, $\delta h = h_{\text{ext}} - h_m$.

§ Equilibration time depends on the degree to which the pressure applied during extraction is greater than the pressure within the sample, or $\delta h = h_{\text{ext}} - h_m$. Larger δh values will require longer equilibration times as the soil recovers from the perturbation incurred during extraction of water.

- When sample saturation is complete, fill the tubing between the ceramic and the burette with the wetting solution. Flush the tensiometer housing and ceramic with the solution until air is removed from the system (Section 3.3.2.3). Fill the burette up to one of the graduations and record this level; cumulative volumes will be determined relative to this first mark.
- Place the sample in contact with the saturated ceramic plate, first ensuring that the valve near the ceramic is closed to prevent water from flowing into sample during the initial setup. Cover both ends of the sample with plastic or foil to minimize evaporation.
- Extract a few milliliters of water from the soil sample into the burette. First, open the valve to the burette and adjust the regulator to a slightly negative gauge pressure (i.e., 0.2–0.5 m more negative than the anticipated matric pressure of the sample). Monitor the level in the burette until the desired volume is withdrawn from the sample.
- After extracting the desired volume of liquid, close the valve under the burette, record the cumulative volume extracted, $\Sigma\Delta V_w$, relative to the first graduation mark recorded in Step 3, and allow the pressure to equilibrate within the sample. Equilibrium is achieved when the pressure readings of the transducer remain stable for a period of several minutes to several

hours, depending on the stage of the experiment. Record the equilibrium matric head, h_m . Note that h_m should be corrected for elevation, since readings are obtained at the location of the transducer ($z = 0$). For example, for the average pressure head reading at the midpoint of the sample, $h_{\text{midpoint}} = h_m - z_1 - z_2$, where z_1 is the vertical distance between the midpoint of the transducer and the top of the ceramic plate and z_2 is equal to one-half the sample length, or $L/2$ (Fig. 3.3.2-7). See also Section 3.3.2.10 for ways to correct the average water content and average h_m of the sample so that they apply to a physical point within the sample.

7. Repeat Steps 5 and 6 until the desired number of points of the retention curve are obtained.
8. After removing the sample from the apparatus, determine the bulk sample volume, V_s , from the sample holder size by using the cylinder dimensions, accounting for any recesses that might be present at the ends. V_s will be used for calculation of volumetric water contents.
9. Oven-dry the sample for 24 to 48 h, or longer for larger samples, at a temperature of 105°C. The initial or saturated water content, θ_s , is then determined from Eq. [3.3.2-4].
10. For each step, convert the cumulative volume change, $\Sigma\Delta V_w$, to cumulative water content change, $\Sigma\Delta\theta$, by dividing by the sample volume, V_s . Calculate θ for each step by subtracting $\Sigma\Delta\theta$ from the saturated water content, θ_s . Pair each θ with the equilibrium h_m values at each step to define the points of the desorption curve.

3.3.2.7.d Comments

The chief purpose of the controlled-volume methods, including the null method, is to achieve faster equilibration, as needed especially for relatively large samples. In the widely used controlled-pressure methods, after each step change in pressure, water must move through the entire sample to equilibrate with the pressure applied at one face. By scaling theory (Miller, 1980), the time required for pressure equilibration in a sample is proportional to the square of the appropriate macroscopic scale length. For the case of pressure equilibration at one face, this would be the sample height. Thus, the common controlled-pressure methods may be most suitable for thin-slab samples. In the controlled-volume methods, however, the equilibration is that of the pressure distribution within the sample itself; this requires less water movement through the sample, and none within the membrane. In this process half of the sample is losing water, the other half gaining. Therefore the appropriate scale length is one-half of the sample height, suggesting that a reduction in equilibration time as high as a factor 4 can be achieved compared with the controlled-pressure methods. The membrane impedance and contact impedance are not involved in the pressure equilibration, which may further reduce the equilibration time. Experiments or numerical analyses of the redistribution process in the sample would give a more accurate indication of this time reduction.

With the technique presented here, hysteresis, generally expected to be negligible, is reflected in the equilibrium h_m . Drainage occurs near the bottom of the sample during extraction of water, with subsequent rewetting during pressure equi-

libration as water redistributes from the upper part of the sample. The resulting h_m would therefore be displaced slightly from the true drying curve. The magnitude of this effect on pressure depends on the sample height, the speed of extraction, and the nature of the soil. For a fairly linear distribution of h_m within the sample, the difference in pressure between the top and bottom of the sample (in units of pressure head), is approximated by the sample length, L . Then, the maximum magnitude of error in h_m would be on the order of L . Reducing the sample height can help to minimize this error. If extraction occurs at a slow enough rate, hysteresis may become insignificant because water will move uniformly downward through the sample and the ceramic plate. In general, the error in pressure introduced by hysteresis should be small relative to the magnitude of pressure being measured.

Errors can occur when determining water contents as a result of inaccuracies in measuring volume outflow. The determination of volumetric water contents depends on the resolution of the graduations on the burette, the ambient room temperature, accuracy in calculation of bulk soil volume, and the presence of air bubbles in the outflow system. With large samples, on the order of 1000 cm³, where large volume increments are used to define θ , relative errors in volume accounting are more tolerable than if smaller samples are used. Since the soil air pressure is always near atmospheric, the range of measurable points is limited to the tensiometer range (Section 3.2.2) and dissolved gases in the water can exsolve out of solution at more extreme negative water pressures, resulting in errors in calculated θ values. Due to the limited range of h_m (<100 kPa suction), supplementary methods, such as those discussed in Section 3.3.2.9, may be required to determine drier points on large samples. For smaller or repacked samples, the pressure plate technique (Section 3.3.2.4) can be used to define additional points.

Several improvements can be made to the procedure and experimental design of the controlled liquid-volume technique. Addition of a bubble-removal system, such as the air-stripper device of Miller and Salehzadeh (1993) or the method outlined in Section 3.3.2.3, would help to decrease errors in volume determination. Insertion of small tensiometers along the length of the sample would allow both hysteresis and nonlinearities in the pressure within the sample to be monitored. The use of short samples decreases the time for water extraction and pressure equilibration, and minimizes hysteresis effects.

Controlled-volume methods have the advantage of being relatively rapid for large samples. With the availability of low cost, fast-responding solid-state transducers, the use of a large tensiometer is practical, and may save time over some of the older controlled-volume null methods where the water level in the burette must be monitored manually in order to determine h_m . Pressure equilibration should be faster with this technique, since approximately half of the sample desaturates during each step. A tradeoff against speed is that the pressure coordinates of the measured points on the retention curve are not known in advance. This technique is suitable whenever faster equilibration times are required, such as when sample size becomes a limiting factor. This method may be attractive for use with large, undisturbed samples, for example, borehole samples, where repacking is undesirable in order to preserve natural structure. However, it can be applied equally well to repacked samples.

3.3.2.8 Determination of Soil Water Characteristic by Freezing Method

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3.3.2.8.a. Introduction

One of the problems with traditional methods for measuring the soil moisture characteristic is that equilibration of soil samples on a pressure plate at lower matric potentials (below approximately -0.5 MPa) requires a long time and is prone to errors. Campbell (1988) examined these problems, which are probably due to both low hydraulic conductivity at those matric potentials and poor hydraulic contact between sample and pressure plate, and concluded that much of the pressure plate data that have been measured and used are probably in error. Spaans and Baker (1996) described an alternative method for obtaining these data by concurrently measuring the liquid water content and temperature over a range of temperatures in a frozen soil sample.

With reversible thermodynamics it can be shown that in a system where ice and liquid water coexist in equilibrium, the water potential of the liquid phase depends on temperature alone, if the gauge pressure of the ice phase is zero. This dependence is very nearly linear, with a slope of approximately $1.2 \text{ kJ kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$. In porous media such as soil, the dependence of the freezing point on water potential means that the soil water freezes incrementally over an extended temperature range. As soil cools, the water in the largest pores freezes first. As the temperature (and water potential) drops further, the ice content increases and the liquid water content decreases. This is embodied in the concept of a freezing characteristic curve, a curve representing concurrent liquid water content and temperature data in a frozen soil.

A soil freezing characteristic is needed to understand transport processes in frozen soil, just as the soil moisture characteristic is required to understand these processes in unfrozen soil. It was proposed that freezing and drying on one hand, and thawing and wetting on the other hand, are very similar processes, since both reflect the water retention properties of soils (Schofield, 1935; Williams, 1964; Miller, 1966). Koopmans and Miller (1966) confirmed this theorem experimentally for two different types of soils. These cardinal developments in frozen-soil science offered the opportunity for using one (measured) relationship to estimate the other.

Lack of reliable methods to measure liquid water content in a frozen soil, however, hampered the development of models simulating transport processes in frozen soil, such as frost heaving. Therefore, the initial focus on the similarity between the two characteristics was to predict the freezing characteristic from the moisture characteristic, but recent advances in new techniques that can discriminate between liquid water and ice in soils, such as TDR, have renewed the interest in this area. With these new techniques it has become possible to measure freezing characteristics directly in the laboratory (Black & Tice, 1989) and in the field (Spaans & Baker, 1996). In addition, it has provided the opportunity to approach the similarity concept between freezing and moisture characteristics from a different perspective, that is to determine soil water retention properties from the freezing technique in the range of water potentials where the drying technique is error prone and tedious.

3.3.2.8.b Matric Potential in Frozen Soil

Water in soils is held by matric forces that lower the Gibb's free energy status of the soil water. *Matric potential* is a conglomerate term for adsorptive forces, exerted by clay particles on the water–mineral interface, and capillary forces, acting at water–air interfaces in pore necks or crevices that connect the inner pore body with the exterior. These same matric forces that retain water also lower the freezing point of that water. Since pure, free water freezes at 0°C, stored water in soils will freeze at temperatures below that. The more tightly it is held, the lower its freezing point. The relationship between the potential (Ψ , kJ kg⁻¹) and the freezing temperature of water (T , in K) is based on thermodynamic principles and can be represented by a generalized form of the Clapeyron equation:

$$d\Psi_L = (\lambda/T)dT + d\Psi_i \quad [3.3.2-9]$$

where λ is the latent heat of fusion of water (334 kJ kg⁻¹ at 0°C), and subscripts “i” and “L” refer to the ice and liquid phases. Note that Ψ is total potential, which is the sum of osmotic (Π) and matric (ψ) potential. In frozen soil, the osmotic potential of ice is zero since it excludes solutes upon formation, while that of the soil liquid water can be inferred from an electric conductivity measurement of a saturated paste extract (σ_{sp} , mS cm⁻¹) of the same soil at room temperature (298 K) (Spaans & Baker, 1996);

$$\Pi_L = -39\sigma_{sp} \left(\frac{W_{sp}\rho_b}{\theta_L\rho_L^2} \right) \left(\frac{T}{298} \right) \quad [3.3.2-10]$$

where W_{sp} is the wetness of the saturated paste (kg kg⁻¹), ρ_b is the bulk density of the soil (kg m⁻³), ρ_L is the density of water (kg m⁻³), and θ_L is the liquid water content (m³ m⁻³).

The gauge pressure of ice is generally assumed to be zero. This is not always true, as evidenced by the tremendous damage that can be caused by frost heave (Miller, 1973, 1980), but in the absence of a ready source of free water (e.g., a water table near the surface) it is usually a reasonable assumption. If the gauge pressure of the ice is zero, an integration of Eq. [3.3.2-9], using the known dependence of λ on T , yields a relatively simple equation to obtain the matric potential in frozen soil from a temperature measurement and one previously determined electrical conductivity measurement (Spaans & Baker, 1996):

$$\begin{aligned} \Psi_L = & -712.38\ln(T/273.15) + 5.545(T - 273.15) \\ & - 3.14 \times 10^{-3}(T^2 - 273.15^2) - \Pi_L \end{aligned} \quad [3.3.2-11]$$

The strong dependence of the matric potential on temperature in frozen soils calls for extremely accurate temperature measurements. Thermocouples can be used, but only with great care avoiding thermal gradients between connections, and assurance that the reference temperature is both highly accurate and representative of the temperature at the reference junction of the thermocouple. Under field conditions, this is difficult to achieve. Thermistors seem to be the preferred sensors, since they are precise, relatively inexpensive, and their resistance changes drasti-

cally with temperature, an order of magnitude more so than for platinum resistance thermometers (PRT). For that same reason their operational temperature range is much narrower than that of other sensors (PRT or thermocouple), but for the temperature range found in soils that is not an issue. Thermistors can easily be multiplexed and automatically measured with data loggers; lead wire resistance is not an issue due to their high resolution. The factory calibrations of thermistors available on the market usually have accuracies (interchangeability) of 0.1 or 0.2°C, which is not good enough for measuring freezing characteristics, so they should be calibrated individually against a secondary temperature standard. The highest accuracy is obtained by measuring thermistors in a six-wire Wheatstone bridge, using accurate reference resistors. The conversion of thermistor resistance (R) to temperature (T) is best done using the Steinhart–Hart equation:

$$(1/T) = a + b \ln R + c (\ln R)^3 \quad [3.3.2-12]$$

where a , b , and c are coefficients unique for every thermistor. As with any thermometer, care should be taken to avoid thermal conduction towards the area of measurement.

3.3.2.8.c Liquid Water Content in Frozen Soil

The measurement of liquid water content in frozen soils is not trivial, since most conventional methods for measuring water content in soils detect total water content and cannot distinguish between liquid water and ice. This includes methods such as gravimetry, neutron thermalization, and gamma densitometry. Nuclear magnetic resonance (NMR) has been employed in laboratory studies of soil freezing to detect liquid water content (Tice et al., 1982), but Oliphant (1985) pointed out that this method is not suitable for in situ measurements since the apparatus disturbs the sample and the flow of heat and water to and from the sample. Furthermore, the method cannot be automated and is expensive, all factors that limit a widespread use of NMR to measure liquid water content in frozen soil.

A promising alternative is time domain reflectometry (TDR; Section 3.1.3). Time domain reflectometry measures the travel time of an electromagnetic wave through soil, which depends on the permittivity of the soil. Since soil is a mixed medium, its permittivity depends on the permittivity of its components, their volumetric fractions and geometric arrangement. The permittivity of liquid water (80) is much higher than that of the other soil components such as soil minerals (4), ice (3), and air (1), which explains the high resolution of TDR for measuring liquid water content in both frozen and unfrozen soils. In addition, TDR can be used both in the field and in the laboratory and can easily be automated, which is an important aspect of winter field work, since thaw events may happen over very short periods of time.

A number of empirical calibration equations to derive water content from travel time measurement in unfrozen soil have been reported (see Section 3.1.3 on TDR), but their applicability to frozen soil has been questioned (Spaans & Baker, 1995). The basis for that argument is that during drying and wetting processes in unfrozen soil, water is interchanged with air. In frozen soil, however, liquid water

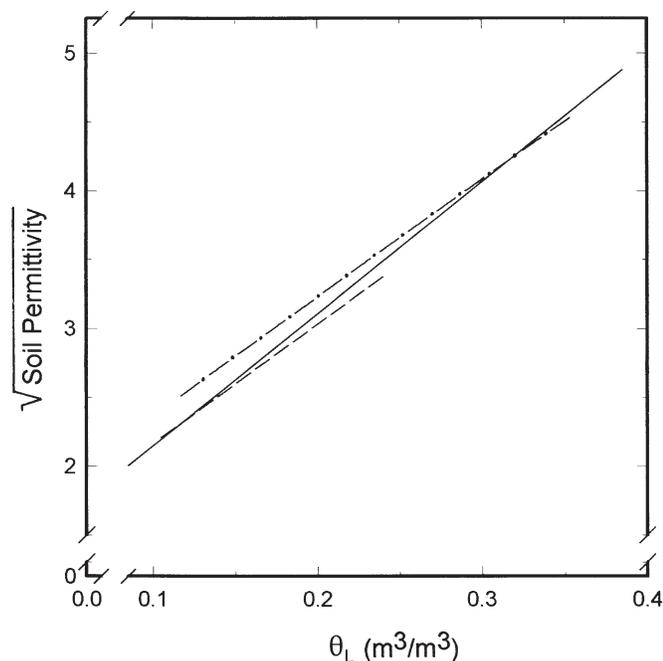


Fig. 3.3.2-8. Comparison of three different calibrations of TDR for liquid water content in a Waukegan silt loam: in unfrozen soil (solid line), in relatively dry, frozen soil (broken line), and in relatively wet, frozen soil (dash-dot line). (Modified from Spaans & Baker, 1995.)

is interchanged with ice, and since the permittivity of ice is higher than that of air, the change in permittivity with respect to liquid water content should be smaller in frozen soil than in unfrozen soil. For the same reason, at equal liquid water contents, the frozen soil is expected to have a higher permittivity than the unfrozen soil, due to the presence of ice. This hypothesis was examined by Spaans and Baker (1995), who designed a gas-dilatometer to calibrate TDR for liquid water content in frozen, undisturbed samples at any degree of water saturation. A gas dilatometer is a closed container with a soil sample inside, subjected to freezing and thawing cycles. The liquid water content is calculated from changes in air pressure inside the gas dilatometer, resulting from the expansion of water as it freezes. The results, shown in Fig. 3.3.2-8, are revealing and demonstrate that the contribution of ice to the permittivity of soil cannot be ignored. Firstly, the calibration curves in relatively dry and wet frozen soil have the same slope but different offset. This was expected, since at any liquid water content the wet soil will contain more ice than the dry soil, which explains why the calibration curve of the wet, frozen soil has a higher offset than the dry, frozen soil. The slopes of the two calibration curves are similar because in frozen soil, changes in liquid water content correspond with changes in ice content, independent of the total amount of ice present. Secondly, the slope of the calibration curve in unfrozen soil is steeper than in frozen soil, due to the fact that the difference in permittivities between water and air is larger than

that between water and ice. Spaans and Baker (1995) concluded that there exists no unique calibration of TDR for liquid water content in frozen soil, but rather a family of calibration curves, all with similar slopes but with offsets that depend on the total water content.

3.3.2.8.d Similarity Between Soil Freezing and Soil Moisture Characteristic

The similarity between freezing and moisture characteristics is not a coincidence, but rather is based on thermodynamic relations (Eq. [3.3.2–11]) to link the temperature in frozen soil to its matric potential, followed by an analysis of similitude between freezing and drying to link the matric potential in frozen soil to that in unfrozen soil. An unfrozen and a frozen soil are *similar* if they have the same (liquid) water content and distribution. Miller (1966) insisted that the similitude analysis can only be applied to air-free frozen soil and ice-free unfrozen soil. Under that scenario, in both soils the adsorptive component of the matric forces is expressed at the mineral–water interface, while the capillary component occurs at the water–air interface in unfrozen state and at the water–ice interface in the frozen state. That means that at similar states the matric potential of adsorbed water is identical in frozen and unfrozen soil. The similitude analysis for capillary water requires more attention. The potential difference across a curved interface is given by:

$$\Delta\psi = 2\gamma/R \quad [3.3.2-13]$$

where γ is the surface free energy between air and liquid water in the unfrozen state (γ_{aL}), and between ice and liquid water in the frozen state (γ_{iL}). The variable R refers to the radius of the largest pore containing liquid water at the current $\Delta\psi$, which in turn, corresponds to $\psi_a - \psi_L$ in the unfrozen state and $\psi_i - \psi_L$ in the frozen state. Typically ψ_L is gauge pressure, so ψ_a is zero, and if ice exists at atmospheric pressure, ψ_i is also zero. Consequently, for the frozen and unfrozen state to be similar, R must be the same; thus, the ratio of the capillary components of the matric potential in unfrozen and frozen soil must be equal to γ_{aL}/γ_{iL} .

Koopmans and Miller (1966) examined this theory by measuring freezing and drying characteristics of the same soil sample, using a Bentonite clay to simulate a soil where the matric forces are purely adsorptive, and fine silt to simulate a soil where matric forces are solely of capillary nature. Using Eq. [3.3.2–9], they converted the temperature in frozen soil to matric potential. For the Bentonite clay the freezing and water characteristic indeed superimposed, confirming that adsorptive forces predominated. The two characteristics of the silt superimposed when the scaling factor γ_{aL}/γ_{iL} assumed a value of 2.2. Consequently, for soils where capillary forces dominate, at similar states of liquid water, the matric potential of the freezing characteristic (Eq. [3.3.2–11]) must be multiplied by a factor 2.2 in order to match it with the corresponding matric potential in the unfrozen soil.

To summarize, the relationship between temperature and matric potential in a frozen soil is clear and unequivocal, and given by Eq. [3.3.2–11]. The uncertainty arises in the similarity of the relationship between water potential and liquid water content in frozen and unfrozen soils. Theory suggests, and evidence confirms, that for adsorbed water the two are exactly equivalent. For capillary water, the ratio of surface free energies must be included. This presents a problem for applying freez-

ing to the determination of a moisture characteristic curve. Unless working with a purely colloidal medium, such as bentonite slurry, or a material such as silt or sand with minimal surface area, where essentially all water is held in capillaries, one does not know which combination of scaling rules to apply to each increment of a measured freezing characteristic to convert it to a moisture characteristic. Most soils contain both capillary and adsorbed water. At the wet end of the moisture characteristic capillary forces generally predominate, while at low matric potentials adsorptive forces are primarily responsible for water retention, with a transition between the two in the intermediate range. Following this reasoning, Spaans and Baker (1996) proposed that freezing would be most applicable to determination of the dry end of the moisture characteristic, with limited utility nearer saturation, where capillary forces are important. This is fortuitous, since it complements the strengths and weaknesses of traditional pressure plate determinations, which are straightforward in the capillary, or wet, region and tedious and error-prone in the adsorbed, dry, region of the moisture characteristic. Spaans and Baker (1996) showed that the freezing characteristic for a Waukegan silt loam (fine silty over sandy, mixed, mesic, typic Hapludoll) did indeed match the moisture characteristic within 1% moisture content at matric potentials below -100 J kg^{-1} without any correction for surface tension effects, assuming zero ice pressure (Fig. 3.3.2–9).

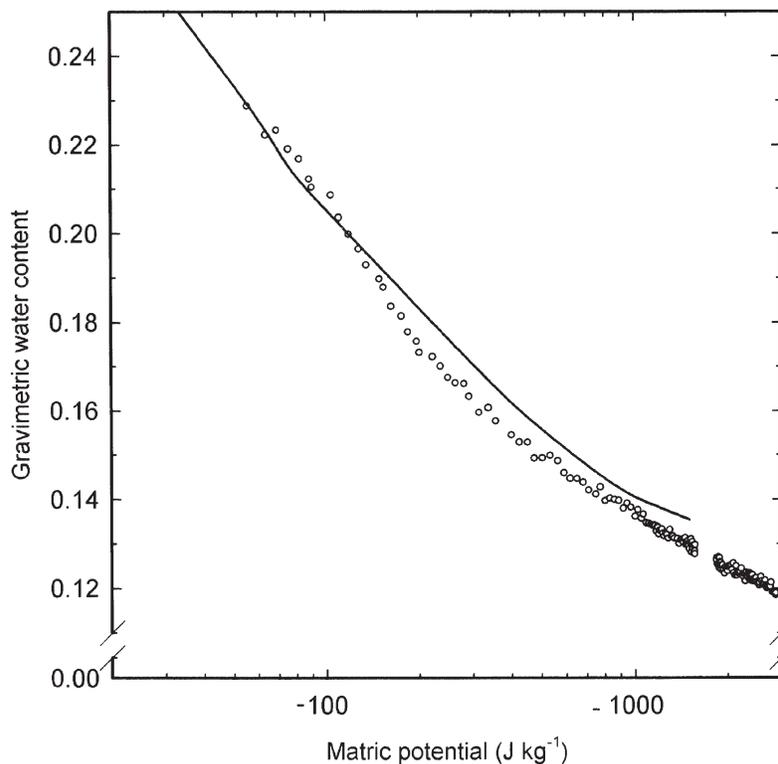


Fig. 3.3.2–9. Soil freezing characteristic (circles) and soil moisture characteristic (solid line) for a Waukegan silt loam. (Modified from Spaans & Baker, 1996.)

3.3.2.8.e Comments

The use of simultaneous measurements of temperature and liquid water content in frozen soil to estimate the dry ($\psi < -100 \text{ J kg}^{-1}$) portion of the moisture characteristic has been demonstrated, and there may soon be commercially available equipment to simplify its application. It offers some potentially powerful advantages for either laboratory determination on small samples or in situ field measurements. However, high accuracy is required in both the temperature and the liquid water content measurements. The latter is still not a trivial measurement and needs additional research. Furthermore, theoretical uncertainty remains regarding the temperature (or water potential) range over which the fraction of capillary water can be considered an insignificant component of the total soil water content.

3.3.2.9 Miscellaneous Methods

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For some purposes the most widely used methods of measuring water retention may be unsuitable or undesirable. For applications under arid conditions, where vapor and liquid flow are both important, a method that covers extremely dry conditions is required. When retention properties of porous rocks are of interest, alternative methods can better accommodate their particular features. Yet other applications, for example, where macropore flow is important, may require a more detailed representation of the retention curve than the common step-equilibration methods can provide. This section briefly describes alternative methods that may serve in cases like these.

3.3.2.9.a Controlled Vapor Pressure—Description and Principles

In this method a small soil sample is placed in a closed chamber that also contains an open vessel with a free salt or acid solution. At equilibrium the soil water attains the same total potential as the water vapor in the free phase, which in turn is in equilibrium with the free solution. The total soil water potential is the sum of the matric and the osmotic potential. For a free solution surface at 15°C , Koorevaar et al. (1983) presented the following form of the Kelvin equation:

$$\ln(p/p_o) = 7.5 \times 10^{-9}(-\Pi) \quad [3.3.2-14]$$

where p is the water vapor pressure (Pa), p_o is the saturated water vapor pressure (Pa) (p/p_o is the relative humidity), and $\Pi = RTc$ is the osmotic pressure (Pa) of the solution, with R being the molar gas constant, T the temperature (K), and c the ionic concentration. Table 3.2.3-1 lists osmotic pressures associated with solutions of practical use. Equation [3.3.2-14] allows the relative humidity to be calculated for known osmotic pressures of the free solution present in the closed chamber. For equal potentials of the soil water and the water vapor, Eq. [3.3.2-14] becomes:

$$\ln(p/p_o) = 7.5 \times 10^{-5}(h_m - h_o) \quad [3.3.2-15]$$

where h_m (m) and h_o (m) are the matric head and the osmotic head of the soil solution, respectively. Assuming $h_o = 0$, the matric head of the soil water can be calculated. Different h_m values can be obtained by controlling the concentrations of the free solution. Repeating the equilibration and determining the water content at the different h_m values associated with various solutions yields a number of points on the water retention curve. The advantage of the method is that it gives retention data in the very dry range. A disadvantage of this method is that it only applies when h_o of the soil water is negligible or when it is at least approximately known. Probably the main impediment to its widespread use is that the method is slow, sometimes requiring 2 to 3 mo at a single step. It was more commonly used in earlier eras, for example, by Thomas (1928) and Robins (1952).

3.3.2.9.b Measured Vapor Pressure—Description and Principles

For determination of dry-range water retention, a more recently favored type of vapor pressure method adjusts the water state without precisely controlling it, for example, by a transient evaporation technique. The water is not in equilibrium with a standard solution, so both θ and h_m must be measured. Gee et al. (1992) used this method with a chilled-mirror humidity sensor to measure h_m . Alternatively, a psychrometer (Section 3.2.3) or other methods described in Section 3.2 could be used. Again, Eq. [3.3.2–15] applies, though only for the purpose of measuring h_m after the potential equilibrates throughout the sample at each step.

Several techniques are possible for adjusting the water state between steps. Suction may be applied through a membrane, but this is usually impractical for dry-range water retention. Evaporation in open air is feasible; heaters or fans can accelerate the process. Ideally the arrangement of heaters and fans should be balanced so that applied heat compensates for evaporative cooling to better maintain isothermal conditions. Osmotic extraction is possible but experimentally complex. For some applications, centrifugation may be practical for the water extraction (Section 3.6.1.1.b). For measuring water content, sample weighing is the preferred method in most cases.

After water extraction at each step, the sample must be sealed up for a time to establish equilibrium conditions. The equilibration required is entirely within the sample, not between the sample and an outside solution. As a result this method is faster than those based on vapor pressure control.

Small samples, on the order of a few grams, are generally required because some types of instrumentation limit sample size. Even when this is not the case, small samples will equilibrate faster, and the unavoidable use of whole-sample averages for θ and h_m is more appropriate for smaller samples. If many small replicate samples are available, there is more experimental flexibility for such options as simultaneous replicate measurements or simultaneous determination of several points on the retention curve. Large samples must be divided carefully to assure adequate representation of the whole (Section 1.4).

3.3.2.9.c Controlled Osmotic Pressure—Description and Principles

An alternative technique uses osmotic equilibration with an osmotic membrane separating a solution, usually polyethylene glycol in water, from direct con-

tact with the soil (Zur, 1966; Pritchard, 1969; Waldron & Manbeian, 1970). After the soil water equilibrates with the osmotic solution, and assuming the matric potential of the osmotic solution equals zero, it follows that

$$h_{m\text{-soil}} + h_{o\text{-soil}} = h_{o\text{-solution}} \quad [3.3.2-16]$$

Therefore, as with the controlled vapor pressure method, if the osmotic head of the soil water ($h_{o\text{-soil}}$) is known, the known osmotic head of the free solution ($h_{o\text{-solution}}$) yields a value for the matric head in the soil ($h_{m\text{-soil}}$). Weighing the sample provides data to determine the water content, and repetition with different solutions gives a number of points on the retention curve.

Membranes for this method can be made of commercially available dialysis materials, typically in the form of tubing. Because polyethylene glycol molecules are large, this sort of membrane can permit most of the molecules normally present in soil solution to pass through, so that the equilibration is actually with the matric head rather than the total head of the soil water. In effect, the $h_{o\text{-soil}}$ term of Eq. [3.3.2-16] is then zero, which eliminates the problem of an unknown osmotic head of the soil solution, as may arise with the vapor-equilibration method.

This method works at matric head values closer to zero than vapor-based methods. It is typically employed for matric head values of less than -100 m; the range is not as extreme as that of vapor equilibration, but drier than is usually practical with most other methods.

Osmotic extraction is likely to be prohibitively slow for all but the smallest samples (a few grams or less). Another limiting factor is that the dialysis membranes to be used for this purpose are fragile and vulnerable to microbiological degradation. There is little published information on this method since about 1970. Since then, however, there have been substantial technological advances in osmotic membranes for dialysis, as well as for desalination, tensiometry, and other applications. These advanced membranes might be advantageous for measuring water retention.

3.3.2.9.d Comments on Vapor-and Osmotic-Based Methods

For the dry range of a retention curve there are not many alternatives to these types of methods. Because the measured vapor pressure method does not require the sample to equilibrate with an imposed standard, this method is faster and hence more widely used than the controlled vapor pressure method. Instead, the measured vapor pressure method has the more easily satisfied requirement that the sample come to a state where its average θ and h_m , as measured by the chosen techniques, both represent a single water state in the sample. The method gains speed at the expense of foreknowledge of the precise h_m values at which retention will be measured. The osmotic pressure method is also practical in its time requirements. It avoids the problem of unknown soil osmotic pressure, and is generally applicable over a somewhat wetter range than the vapor methods.

Typically, small samples are used in these methods in order to minimize equilibration times. Small samples are particularly sensitive to perturbations of θ or h_m during weighing or other operations, so caution in handling is necessary. Prepara-

tion procedures normally destroy the soil structure of small samples. The resulting alteration of properties, however, is likely to be less problematic for the dry portions of the curve, where adsorbed water that coats particle surfaces in thin films is more important than water in filled pores. Vapor and osmotic phenomena are particularly sensitive to temperature variations. Some degree of protection from air temperature fluctuations, and also from fluctuations in radiant heating from ordinary light (Robins, 1952), is usually necessary in the application of these methods.

3.3.2.9.e Transient Liquid-Phase Methods

Most retention methods proceed in discrete equilibration steps, but not all applications require this. Transient methods, sometimes called *dynamic* or *unsteady* methods, change the water state of the soil in a controlled and continuous way, usually with applied suction. The soil water is not in equilibrium with an established pressure, so these methods require simultaneous measurement of both h_m and θ during the changing conditions. The pairing of these measurements represents a transient retention curve. This curve may differ from curves measured by equilibrium and steady-flow techniques, but it is not well established how great the transient vs. equilibrium retention differences are (Davidson et al., 1966; Topp et al., 1967; Rogers & Klute, 1971). Transient methods are relatively fast because there is no waiting for equilibration, and the sample can be taken through wetting and drying cycles as fast as its properties and the time resolution of the instrumentation will allow.

Most of these methods resemble the experiments of Topp and Miller (1966) and Bomba (1968), who used transient methods to measure both retention and the unsaturated hydraulic conductivity of glass bead samples. Perroux et al. (1982) developed a similar technique for use with natural soils, as did Nimmo and Miller (1986) with an apparatus later improved by Salehzadeh (1990). Section 3.6.2 describes additional inverse methods that are essentially transient in nature.

The design and implementation of transient or dynamic methods is not standardized, so one should consult the original references. The required elements are (i) a means of controlling the applied matric head, ideally according to a preset program; (ii) a point-like h_m measurement, usually made with tensiometers; and (iii) a point-like θ measurement, made, for example, using gamma-ray attenuation (Section 7.2.2.1). The pressure control frequently involves an air tank that is slowly filled or emptied to change its pressure, and that is linked in some way to the soil matric head. Recent innovations include computer-controlled valves to make an easily programmed pressure controller (Zurmühl, 1998). The h_m and θ measurements must be made simultaneously for the same small portion of the sample, so fast-response, high-resolution instruments are essential. For h_m , small tensiometers equipped with solid-state pressure transducers are suitable. For θ , gamma-ray attenuation is generally the best choice. Certain types of time domain reflectometry (TDR) apparatus, such as that of Kelly et al. (1995) or Nissen et al. (1998), may also be suitable.

Once operational, transient methods are a fast way to obtain retention curves, sometimes the fastest practical means. They easily produce large numbers of

closely spaced measured points, giving a high level of resolution that may be useful in assessing the effects of soil structure. They lend themselves to concurrent Darcian unsaturated conductivity (K) measurements (Topp & Miller, 1966) and to the measurement of soil water hysteresis. It is possible to determine both drying and wetting curves, main and scanning, through appropriate implementation of the pressure-control program. For use with fine-textured media or for low θ conditions, transient methods are most suitable for samples in the form of thin slabs. The heterogeneities of undisturbed core samples may be tolerable if the geometry of the regions of h_m and θ measurement is well defined. A significant disadvantage is the need for specialized equipment.

3.3.2.10 Computational Corrections

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Accurate determination of the matric head–volumetric water content, $h_m(\theta)$, relation is important for modeling soil water movement. Richards' equation, which describes the movement of water in porous media, is solved assuming knowledge of the unsaturated hydraulic properties determined at physical points, also referred to as *macroscopic volume elements*. Because a soil sample has a finite height, the data obtained with some of the methods described above are not applicable at a physical point; that is, the data pertain to an average volumetric water content, $\bar{\theta}$, for the sample as a whole, and the corresponding matric head is defined by

$$\bar{h}_m = (\bar{P}_w - \bar{P}_a)/(\rho_w g) \quad [3.3.2-17]$$

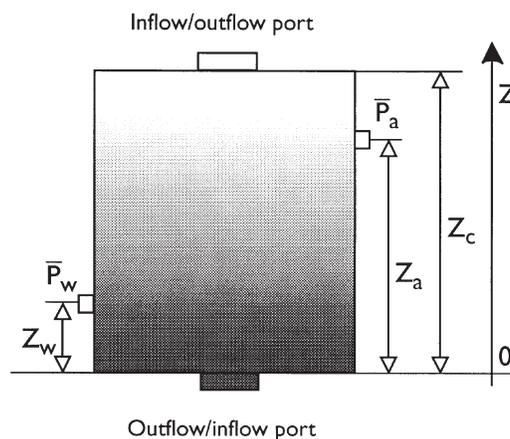


Fig. 3.3.2-10. Simplified pressure cell diagram as used in the correction procedure to obtain physical point retention data from averaged pressure cell data.

where \bar{P}_w (kPa) is the water pressure measured at elevation z_w (m), and \bar{P}_a (kPa) the air pressure measured at elevation z_a (Fig. 3.3.2–10). It should be noted that z_w should correspond to the elevation at which h_m is determined as outlined under any of the previously determined procedures. Traditionally, the measured $\bar{\theta}(\bar{h}_m)$ relation has been assumed to be applicable at a physical point. Although this assumption is most likely accurate enough for soil water–air systems in porous media with a gradual change in pore size, it can be highly inaccurate in relatively coarse porous media (Dane et al., 1992). In the former cases a reasonably uniform distribution of water content exists in a soil sample. In the latter cases, however, a considerably nonuniform distribution of water in the vertical direction may exist in a soil sample, which yields inaccurate results. In other words, the samples cannot be treated as physical or macroscopic points. To overcome this inaccuracy in determining the matric head–volumetric water content relation, Liu and Dane (1995a) developed a relation between the volumetric water content and capillary pressure head values ($h_c = -h_m$) obtained with a relatively tall sample and those that are applicable at a physical point. To make the development of this relation possible, Liu and Dane (1995a) assumed the validity of the Brooks and Corey (1964) relation:

$$\begin{aligned}\theta &= \theta_r + (\theta_s - \theta_r)(h_d/h_m)^\lambda && \text{for } h_m \leq h_d \\ \theta &= \theta_s && \text{for } h_m > h_d\end{aligned}\quad [3.3.2-18]$$

where λ (–) is the pore size distribution index, θ is the volumetric water content, θ_s is the saturated water content, θ_r is residual volumetric water content, h_d (m) is the displacement matric head (air entry value), and the matric head, h_m , is defined by Eq. [3.3–2]. It should be noted that all variables used in Eq. [3.3.2–18] and Eq. [3.3–2] now clearly apply at a physical point. The Brooks–Corey parameters that define the water retention curve are θ_r , θ_s , h_d , and λ . Once these parameters are known, the $\theta(h_m)$ relation is completely determined. In Eq. [3.3.2–18], the value for the saturated water content is assigned to the saturated water content; that is, $\theta_s = \theta_0$. The expression relating $\bar{\theta}(\bar{h}_m)$ to $\theta(h_m)$ is of the general form (Liu & Dane, 1995a):

$\bar{\theta} = f(\bar{h}_m; \text{pressure cell configuration};$

$$\text{fluid densities; Brooks–Corey parameters}) \quad [3.3.2-19]$$

Liu and Dane (1995a) outlined how Eq. [3.3.2–19] can be used in a curve fitting procedure to obtain the Brooks–Corey parameters as they apply to a physical point. It should be noted that Liu and Dane (1995a) used capillary pressure head (h_c) rather than matric head ($h_m = -h_c$). A computer program was developed (Liu & Dane, 1995b) to make the transfer from an “averaged” retention relation to one that applies at a physical point, given the configuration of the pressure cell or hanging water column apparatus. This program was later modified to a Windows, menu-driven version called TrueCell (Jalbert et al., 1999), which is available upon request or can be downloaded from the Soil Physics web site at Auburn University (<http://www.ag.auburn.edu/dept/ay/sp>).

Table 3.3.2–2. Characteristics of water retention measurement methods.

Method	Suitable types of samples [†]	Typical range of matric head values [‡]	Typical time requirements (for whole curve)	Cost of apparatus and supplies	Difficulty of apparatus and supply procurement [§]	Difficulty of setup	Difficulty of operation
Hanging column	Small cores or repacked samples	0 to –8.5 m	Low	Very low	Very low	Low	Low
Pressure cell	Small cores or repacked samples	0 to –8.5 m	Medium	Low	Very low	Low	Low to medium
Pressure plate	Thin slabs	0 to –150 m [¶]	Medium to high	Low	Very low	Low	Low to medium
Long column	Homogeneous packed samples	0 to –8.5 m [#]	Medium	High	Medium to high	Medium to high	Medium to high
Suction table	Small cores or repacked samples	0 to –5 m	Medium to high	Low to medium	Medium	Medium	Low
Controlled volume	Small-to-medium cores or repacked samples	0 to –8.5 m ^{††}	Medium	Low to medium	Medium	Low to medium	Low to medium
Controlled vapor pressure	Small cores or repacked samples	–500 to –50000 m	High	Very low	Low	Low	Low
Controlled osmotic pressure	Very small cores or repacked samples	–1 to –300 m	Medium	Low	Medium	Medium to high	Medium
Measured vapor pressure	Small cores or repacked samples	–100 to –50000 m	Medium	Medium	Low	Low	Medium
Transient	Small-to-medium cores or repacked samples	0 to –30 m	Low	Medium to high	Medium	Medium to high	Medium to high

[†] “Small” indicates diameter of a few cm, “medium” about 10–20 cm.

[‡] Ranges are for versions of methods described in this chapter.

[§] For versions of methods described in this chapter.

[¶] Assuming equilibration at an applied pressure of 150 m is possible.

[#] Larger range possible with modifications.

^{††} Approximate, since volume rather than pressure is controlled.

Table 3.3.2–3. Low–high criteria for relative evaluations of water retention methods.

Entry notation	Time requirements	Cost [†]	Difficulty of procurement	Difficulty of initial setup [‡]	Difficulty of operation
Low	Few hours to few days	<~\$1000	All components commercially available	Few hours to few days	Requires intermittent attention and common skills (e.g. weighing, reading instruments)
High	Several weeks to several months	>~\$5000	Significant portion of needed apparatus must be specially fabricated or modified	Few weeks	Requires nearly continuous attention or unusual skills (e.g., adjusting gamma-ray detection equipment)

[†] Cost estimates are in 1999 U.S. dollars. Costs listed here are for basic apparatus required to do measurements on a minimum number of samples. Costs are only for apparatus particular to the method in question, assuming the measurements are to be done in a lab equipped with balances, ovens, compressed air, data-acquisition systems, and other items generally involved in common soil physical measurements.

[‡] Time required for setup is estimated assuming needed components are at hand and personnel have the skills and knowledge required.

3.3.2.11 Guidelines For Method Selection

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Table 3.3.2–2 lists suggested guidelines that may be helpful in choosing among the various water retention measurement methods described in Section 3.3.2. The entries in the table compare such characteristics as the possible measurement range, time, cost, and difficulty of use. In most categories, evaluations are made only on a relative basis. The headings of the five categories with “low–medium–high” evaluations are formulated to maintain a consistent pattern, “low” being more favorable than “high.”

Unavoidably, this selection guide reflects subjective judgment. To help interpret and understand these judgments, Table 3.3.2–3 describes the main criteria applied for the categories where subjectivity is most likely to be a factor.

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