

LAB #3 – Measurement of Soil Water Characteristic Curve – Sensor Pairing and Laboratory Methods

(Environmental Measurements CE/ENVE 320-04)

Objectives

The purpose of the lab is to introduce students to the state-of-the-art methods used for determination of Soil Water Characteristic (SWC) curve that relates matric potential (ψ_m) and volumetric water content (θ_v). Students will employ a combination of field techniques such as sensor pairing using TDR and tensiometers coupled with laboratory methods to obtain data points that will serve as a basis for parametric model estimation and assessment of data quality and limitations.

The specific objectives are:

- (1) To use pressure flow cells (Tempe cells) containing disturbed soil samples to determine the matric potential – volumetric water content (ψ_m - θ_v) relationship for the matric potential (ψ_m) range of from 0 to -10 m (-1 bar).
- (2) To use a pressure plate device (Richard's pressure plate apparatus) and disturbed soil samples to obtain ψ_m - θ_v pairs for the ψ_m range from -10 to -30 m (-3 bar or -0.3 MPa).
- (3) To use a Dewpoint Potentiometer to obtain ψ_m - θ_v pairs for the ψ_m range from -50 to -150 m (-15 bar or -1.5 MPa).
- (4) To install tensiometers and TDR probes in a soil column (simulating a soil profile in the field) and obtain simultaneous measurements of matric potential (tensiometers) and volumetric water content (TDR) to establish SWC in-situ).
- (5) To combine the results, construct a SWC curve, and fit parametric models to the combined measurements and discuss the results.

Theoretical Background

Soil Water Characteristic (SWC)

The soil water characteristic (SWC) describes the functional relationship between soil water content (θ_m or θ_v) and matric potential under equilibrium conditions. The SWC is an important soil property related to the distribution of pore space (sizes, interconnectedness), which is strongly affected by texture and structure, as well as related factors including organic matter content. The SWC is a primary hydraulic property required for modeling water flow, for irrigation management, and for many additional applications related to managing or predicting water behavior in the porous system. A SWC is a highly nonlinear function and is relatively difficult to obtain accurately. Because the matric potential extends over several orders of magnitudes for the range of water contents encountered in the field, the matric potential is often plotted on a logarithmic scale. Fig.1-1 depicts several SWC

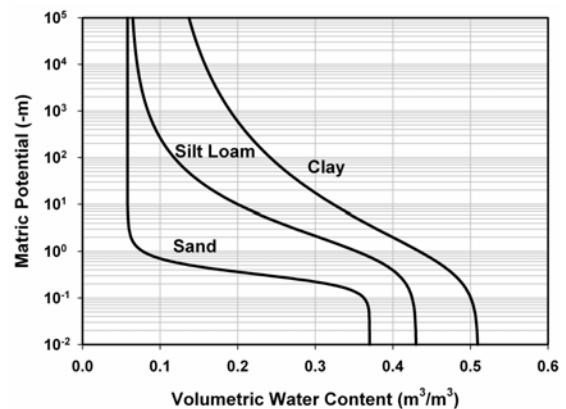


Fig.1-1: Soil water characteristic curves for soils of different texture.

curves for soils of different textures demonstrating the reduced porosity (saturated water content) and the relatively large pores for coarse-textured media such as sand.

Measurement of SWC Curves

Several methods are available to obtain the measurements required for SWC estimation. The basic requirement is for pairs of ψ_m - θ measurements over the wetness range of interest. Among the primary experimental problems in determining a SWC are: (i) the limited functional range of the tensiometer, which is often used for in-situ measurements; (ii) inaccurate or imprecise θ_v field measurements (no longer as significant a problem due to availability of TDR); (iii) the difficulty in obtaining undisturbed samples for laboratory determinations; and (iv) a slow rate of equilibrium under low matric potential values associated with dry soils.

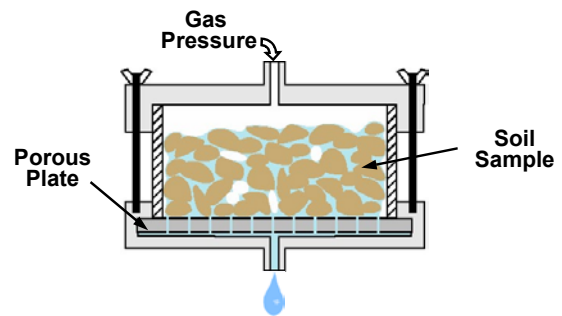
In-situ (in place) methods are considered the most representative techniques for determining SWC's, particularly when a wide range of ψ_m - θ values are obtained. An effective method for obtaining simultaneous measurements of ψ_m and θ_v utilizes TDR probes installed in the soil at close proximity to transducer tensiometers, and recording the changing values of each attribute through time as the soil wetness varies. Large changes in ψ_m and θ_v can be induced under highly evaporative conditions (e.g., a fan), or in the presence of active plant roots.

Laboratory Measurements with Pressure Flow Cell and Pressure Plate

The pressure plate apparatus consists of a pressure chamber enclosing a water-saturated porous plate, which allows water but prevents air flow through its pores (Fig.1-2). The porous plate is open to atmospheric pressure at the bottom surface, while the top surface is at the applied pressure of the chamber. Sieved soil samples (<2mm) are placed in retaining rubber rings in contact with the porous plate and left to saturate in water. After saturation is attained, the porous plate with the saturated soil samples is placed in the chamber and a known gas (commonly N_2 or air) pressure is applied to force water out of the soil and through the plate. Flow continues until equilibrium between the force exerted by the air pressure and the force by which soil water is being held by the soil (ψ_m) is reached.

Soil water retention in the low suction range of 0 to 10 m (0-1 bar) is strongly influenced by the soil structure and its natural pore size distribution. Hence, "undisturbed" intact soil samples (cores) are preferred over repacked samples. The pressure flow cell (also known as Tempe cell) can hold intact soil samples encased in metal rings. The operation of the cell follows that of the pressure plate, except the pressure range for the Tempe cell is usually lower, 0 to 10 m (1 bar or 0.1 MPa). The porous ceramic plates for both the pressure plate and the flow cell must be completely saturated, a process which may take a few days to achieve. Following equilibrium between soil

(a) Pressure/Flow Cell (Tempe Cell)



(b) Pressure Plate

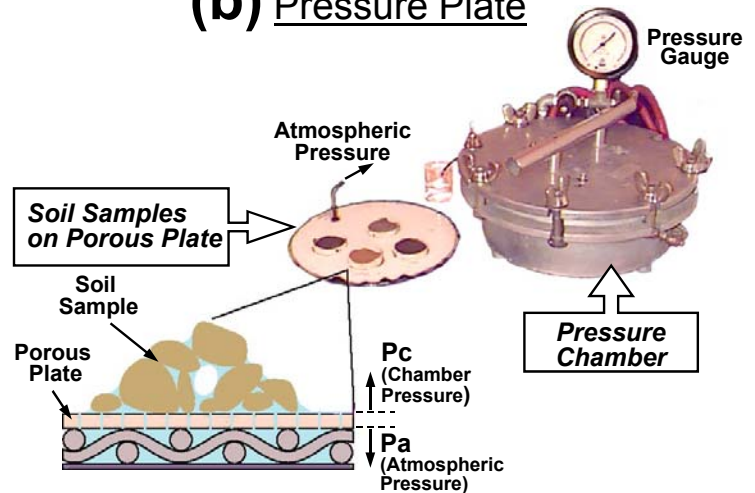


Fig.1-2: (a) Pressure and flow cell (Tempe cell); and (b) pressure plate apparatus used to desaturate soil samples to desired matric potential.

matric potential and the applied air pressure, the soil samples are removed from the pressure plate, weighed, and oven dried for gravimetric determination of water content. An estimate of the sample's bulk density must be provided to convert θ_m to θ_v in the case of disturbed samples.

Several pressure steps may be applied to the same samples when using flow cells. The cells may be disconnected from the air pressure source and weighed to determine the change in mass hence water content from the previous step, then reconnected to the air pressure and a new higher pressure step applied. Outflow from the cells may also be monitored and related to the change in the sample's water content.

Relative Humidity and Thermocouple Psychrometry

Under equilibrium conditions the soil water potential is equal to the potential of water vapor in the ambient soil-air. A psychrometer can measure the relative humidity (RH) of the water vapor which is related to the water potential (ψ_w) of the vapor through:

$$RH = \frac{e}{e_0} = \exp \frac{M_w \psi_w}{\rho_w R T} \quad (1)$$

where e is water vapor pressure, e_0 is saturated vapor pressure at the same temperature, M_w is the molecular weight of water (0.018 kg/mol), R is the ideal gas constant (8.31 J K⁻¹ mol⁻¹ or 0.008314 kPa m³ mol⁻¹ K⁻¹), T is absolute temperature (K), and ρ_w is the density of water (1000 kg/m³ at 20 °C). Rearranging and taking a log-transformation of Eq.(1) yields an expression for ψ_w :

$$\psi_w = \frac{R T \rho_w}{M_w} \ln \left(\frac{e}{e_0} \right) \quad (2)$$

Eq.(2) can be further simplified for the range of e/e_0 near 1 often encountered in agricultural soils; the entire range of plant-available water is between $e/e_0=0.98$ and 1.0:

$$\psi_w = \frac{R T \rho_w}{M_w} \left(\frac{e}{e_0} - 1 \right) \approx 462 T \left(\frac{e}{e_0} - 1 \right) \quad (3)$$

for ψ_w in kPa. Note that because most salts are non volatile, the vapor based measurement of the soil's ψ_w is the sum of the osmotic and matric potentials ($\psi_w = \psi_m + \psi_s$). The soil-air interface acts as a diffusion barrier in allowing only water molecules to pass from liquid to vapor state.

Several methods are available for determination of relative humidity. A psychrometer infers the relative humidity from the difference between *dry bulb* and *wet bulb* temperatures. The *dry bulb* is the temperature of the ambient air (non-evaporating surface), and the *wet bulb* is the temperature of an evaporating surface which is generally lower than the dry bulb temperature because of latent heat loss in the evaporation process. The relative humidity determines the rate of evaporation from the wet bulb junction, and thus the extent of temperature depression below ambient or dry bulb temperature.

A thermocouple psychrometer consists of a fine wire chromel-constantan or other standard bimetallic thermocouple. A thermocouple is a double junction of two dissimilar metals. When the two junctions are subjected to different temperatures they generate a voltage difference explained as the *Seebeck effect*. Conversely, when an electrical current is applied through the junctions it creates a temperature difference between the junctions by heating one while cooling the other, depending on the current's direction.

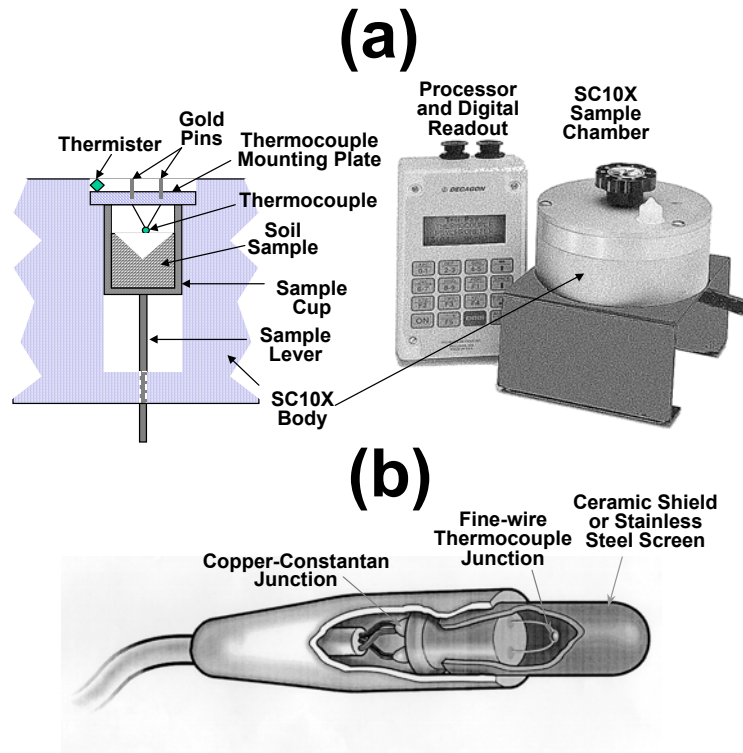


Fig.1-3: (a) SC10X sample chamber for psychrometric laboratory measurements of soil water potential (Source: Decagon Devices Inc., Pullman, WA); and (b) A field psychrometer with porous ceramic shield (Source: Wescor Inc., Logan, UT)

For typical soils use, one junction of the thermocouple psychrometer is suspended in a thin-wall ceramic or stainless steel cup buried in the soil (Fig.1-3b), while the other is embedded in an insulated plug to measure the ambient temperature at the same location. In *psychrometric mode*, the suspended thermocouple is cooled below the dew point by means of an electrical current until pure water condenses on the junction. This is called *Peltier* cooling. The cooling then stops, and as water evaporates it draws heat in the form of latent heat of vaporization from the junction, depressing it below the temperature of the surrounding air until it attains a *wet bulb* temperature. The warmer and dryer the surrounding air, the higher the evaporation rate and the greater the wet bulb depression. The difference in temperatures between the insulated *dry bulb* and the *wet bulb* thermocouples is measured and used to infer the relative humidity or relative vapor pressure using the psychrometer equation:

$$RH = \frac{e}{e_0} = 1 - \frac{s + \gamma}{e_0} \Delta T \quad (4)$$

where s is the slope of the saturation water vapor pressure curve ($s = de_0/dT$), γ is the psychrometric constant (about 0.067 kPa K^{-1} at 20°C), and ΔT is the temperature difference (K). The slope s is temperature-dependent and can be approximated from (Brutsaert, 1982):

$$\frac{de_0}{dT} = \frac{373.15e_0}{T^2} \left(13.3185 - 3.952t_R - 1.9335t_R^2 - 0.5196t_R^3 \right) \quad (5)$$

where $t_R = 1 - 373.15/T$. The saturated vapor pressure e_0 is also temperature dependent and is estimated from the integral of Eq.(5):

$$e_0 = 101.325 \exp(13.3185 t_R - 1.9760 t_R^2 - 0.6445 t_R^3 - 0.1299 t_R^4) \quad (6)$$

The relationship between e , T , and RH is uniquely defined, so that knowledge of any two leads to the third quantity. Furthermore, the relationship between e and vapor density (ρ_v), the mass of water vapor per unit volume of air, is based on the ideal gas law as:

$$\rho_v = \frac{m_w}{V_a} = \frac{e}{4.62 \times 10^{-4} T} \quad [\text{g}/\text{m}^3] \quad (7)$$

For Eqs.(4) to (7), T is in Kelvin = $273.15 + ^\circ\text{C}$. The relationships between temperature, pressure, and relative humidity may be conveniently expressed in graphical format, e.g.

A typical temperature depression measurable by a good psychrometer is on the order of $0.000085 \text{ }^\circ\text{C}$ per kPa. This means that any errors in measuring wet bulb depression can introduce large errors into psychrometric determinations. Thermal equilibrium is therefore a prerequisite for obtaining reliable readings, as any temperature difference between wet and dry sensors resulting from thermal gradients will be erroneously incorporated into the relative humidity calculation.

A second means of inferring relative humidity and thus water potential using thermocouple psychrometers is called the *dew point method*. This is based on the principle that the wet thermocouple junction would not lose or gain any water if held precisely at the dew point temperature. Electronic monitoring and control circuitry is employed to essentially do just this, through a feedback system whereby the junction temperature is constantly measured and the applied cooling current adjusted accordingly. Note that ambient heat transfer mechanisms other than evaporation and condensation must be nullified (compensated for) in order to achieve this balance.

Summarizing, psychrometric measurements of soil water potential are based on equilibrium between liquid soil water and water vapor in the ambient soil atmosphere. The drier the soil, the fewer water molecules "escape" into the ambient atmosphere, resulting in lower vapor pressure and relative humidity. When the osmotic potential is very small, the soil water potential measured by a psychrometer is approximately equal to the soil matric potential.

Field Measurement Methods for SWC Estimation - Sensor Pairing

Despite the paramount importance of SWC determination in situ, suitable measurement techniques are severely lacking at present. The most common approach is to use paired sensors such as TDR waveguides and tensiometers to determine soil water content and matric potential simultaneously and in the same soil volume. Let us first introduce the sensors before discussing the merits and limitations of the method,

Time Domain Reflectometry

Time Domain Reflectometry (TDR) is a relatively new method for measurement of soil water content. Its first application to soil water measurements was reported by Topp et al. (1980). The main advantages of the TDR method over other methods for repetitive soil water content measurement such as the neutron moisture meter are: (i) superior accuracy to within 1 or 2% of volumetric water content; (ii) calibration requirements are minimal - in many cases soil-specific calibration is not needed; (iii) averts radiation hazards associated with neutron probe or gamma-attenuation techniques; (iv)

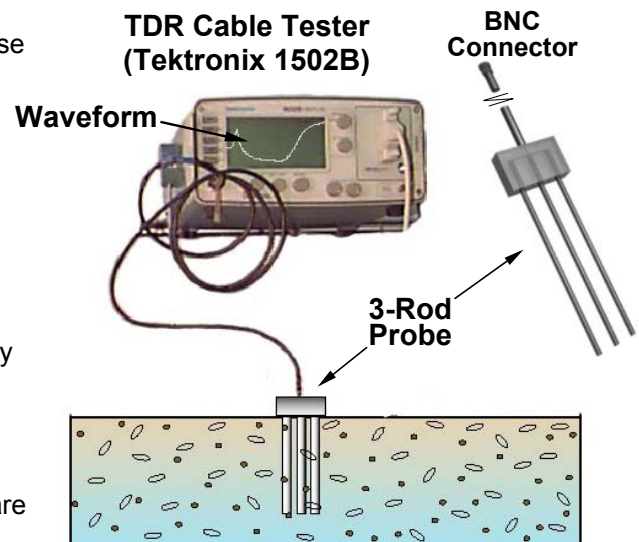


Fig.1-4: TDR cable tester with 3-rod probe embedded vertically in surface soil layer.

excellent spatial and temporal resolution; and (v) measurements are simple to obtain, and the method is capable of providing continuous soil water measurements through automation and multiplexing.

The propagation velocity (v) of an electromagnetic wave along a transmission line (probe or waveguide) of length L embedded in the soil is determined from the time response of the system to a pulse generated by the TDR cable tester. The propagation velocity ($v=2L/t$) is a function of the soil bulk dielectric constant (ϵ_b) according to

$$\epsilon_b = \left(\frac{c}{v} \right)^2 = \left(\frac{c t}{2 L} \right)^2 \quad (8)$$

where c is the velocity of electromagnetic waves in vacuum (3×10^8 m/s), and t is the travel time for the pulse to traverse the length of the embedded waveguide (down and back = 2L). The definition of the dielectric constant is given in Eq.(8); it simply states that the dielectric constant of a medium is the ratio squared of propagation velocity in vacuum relative to that in the medium. The soil bulk dielectric constant (ϵ_b) is governed by the dielectric of liquid water $\epsilon_w \cong 81$, as the dielectric constants of other soil constituents are much smaller, e.g., soil minerals $\epsilon_s=3$ to 5, frozen water (ice) $\epsilon_i=4$, and air $\epsilon_a=1$. This large disparity of the dielectric constants makes the method relatively insensitive to soil composition and texture and thus a good method for liquid soil water measurement. Note that because the dielectric constant of frozen water is much lower than for liquid, the method may be used in combination with a neutron probe or other technique which senses total soil water content, to separately determine the volumetric liquid and frozen water contents in frozen or partially-frozen soils (Baker and Allmaras, 1990).

Two basic approaches have been used to establish the relationships between ϵ_b and volumetric soil water content (θ_v). The first approach is empirical, whereby mathematical expressions are simply fitted to observed data without using any particular physical model. Such an approach was employed by Topp et al. (1980) who fitted a third-order polynomial to the observed relationships between ϵ_b and θ_v for multiple soils. The second approach uses a model of the dielectric constants and the volume fractions of each of the soil components to derive a relationship between the composite (bulk) dielectric constant and soil water (i.e., a specific component). Such a physically-based approach, called a dielectric mixing model, was adopted by Birchak (1974) and Roth et al. (1990).

TDR calibration establishes the relationship between ϵ_b and θ_v . For this discussion we assume that calibration is conducted in a fairly uniform soil without abrupt changes in soil water content along the waveguide. The empirical relationship for mineral soils as proposed by Topp et al. (1980):

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \epsilon_b - 5.5 \times 10^{-4} \epsilon_b^2 + 4.3 \times 10^{-6} \epsilon_b^3 \quad (9)$$

provides adequate description for the water content range <0.5 , which covers the entire range of interest in most mineral soils, with an estimation error of about 0.013 for θ_v . However, Eq.(9) fails to adequately describe the ϵ_b - θ_v relationship for water contents exceeding 0.5, and for organic soils or mineral soils high in organic matter, mainly because Topp's calibration was based on experimental results for mineral soils and concentrated in the range of $\theta_v < 0.5$. Birchak et al., (1974) and Roth et al. (1990) proposed a physically-based calibration model which considers dielectric mixing of the constituents and their geometric arrangement. According to this mixing model the bulk dielectric constant of a three-phase system may be expressed as:

$$\epsilon_b = \left[\theta_v \epsilon_w^\beta + (1 - n) \epsilon_s^\beta + (n - \theta_v) \epsilon_a^\beta \right]^{1/\beta} \quad (10)$$

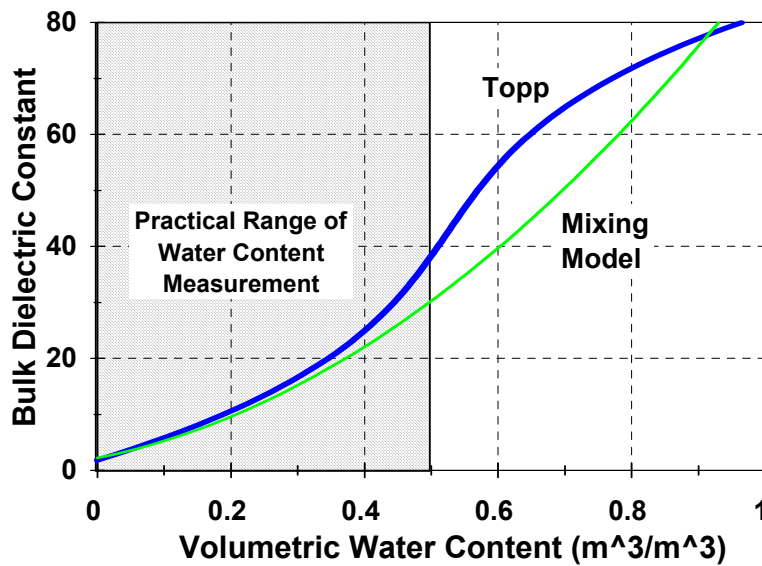


Fig.1-5: Relationships between bulk soil dielectric constant and θ_v expressed by two commonly used TDR calibration approaches

where n is the soil's porosity, $-1 < \beta < 1$ summarizes the geometry of the medium in relation to the axial direction of the wave guide ($\beta=1$ for an electric field parallel to soil layering, $\beta=-1$ for a perpendicular electrical field, and $\beta=0.5$ for an isotropic two-phase mixed medium), $1-n$, θ_v and $n-\theta_v$ are the volume fractions and ϵ_s , ϵ_w and ϵ_a are the dielectric constants of the solid, aqueous and gaseous phases, respectively. Note that $\theta_v = V_w/V_T$, $(1-n) = V_s/V_T$, and $(n-\theta) = V_{air}/V_T$, so these components sum to unity. Rearranging Eq.(10) and solving for θ_v yields

$$\theta_v = \frac{\epsilon_b^\beta - (1-n)\epsilon_s^\beta - n\epsilon_a^\beta}{\epsilon_w^\beta - \epsilon_a^\beta} \quad (11)$$

which determines the relationship between ϵ_b measured by TDR and θ_v . Many have used $\beta=0.5$ which is shown by Roth et al. (1990) to produce a calibration curve very similar to the third-order polynomial proposed by Topp for the water content range of $0 < \theta_v < 0.5$. If we introduce into (11) common values for the various constituents such as $\beta=0.5$, $\epsilon_w=81$, $\epsilon_s=4$, and $\epsilon_a=1$ we obtain the simplified form

$$\theta_v = \frac{\sqrt{\epsilon_b} - (2-n)}{8} \quad (12)$$

Note that the soil's porosity must be known or estimated when using the mixing model approach. A comparison between Topp's expression (Eq.(9)) and a calibration curve based on Eq.(10) with $n=0.5$ is depicted in Fig.1-5. Summarizing, Eq.(9) establishes an empirical relationship between bulk soil dielectric and volume water content, while Eqs.(8) and (10) are based on physical and geometrical considerations. Eq.(12) provides a simplified version of (10).

Limitations or disadvantages of the TDR method include relatively high equipment expense, potential limited applicability under highly saline conditions due to signal attenuation, and the fact that soil-specific calibration may be required for soils having large amounts of bound water or high organic matter contents.

Tensiometer for Soil Matric Potential (ψ_m) Measurement

A tensiometer consists of a porous cup, usually made of ceramic and having very fine pores, connected to a vacuum gauge through a water-filled tube (Fig.1-6).

The porous cup is placed in intimate contact with the bulk soil at the depth of measurement. When the matric potential of the soil is lower (more negative) than inside the tensiometer, water moves from the tensiometer along a potential energy gradient to the soil through the saturated porous cup, thereby creating suction sensed by the gauge. Water flow into the soil continues until equilibrium is reached and the suction inside the tensiometer equals the soil matric potential. When the soil is wetted, flow may occur in the

reverse direction, i.e., soil water enters the tensiometer until a new equilibrium is attained. The tensiometer equation is:

$$\psi_m = \psi_{\text{gauge}} + (z_{\text{gauge}} - z_{\text{cup}}) \quad (13)$$

with ψ_{gauge} the reading at the vacuum gauge location and z indicating depth.

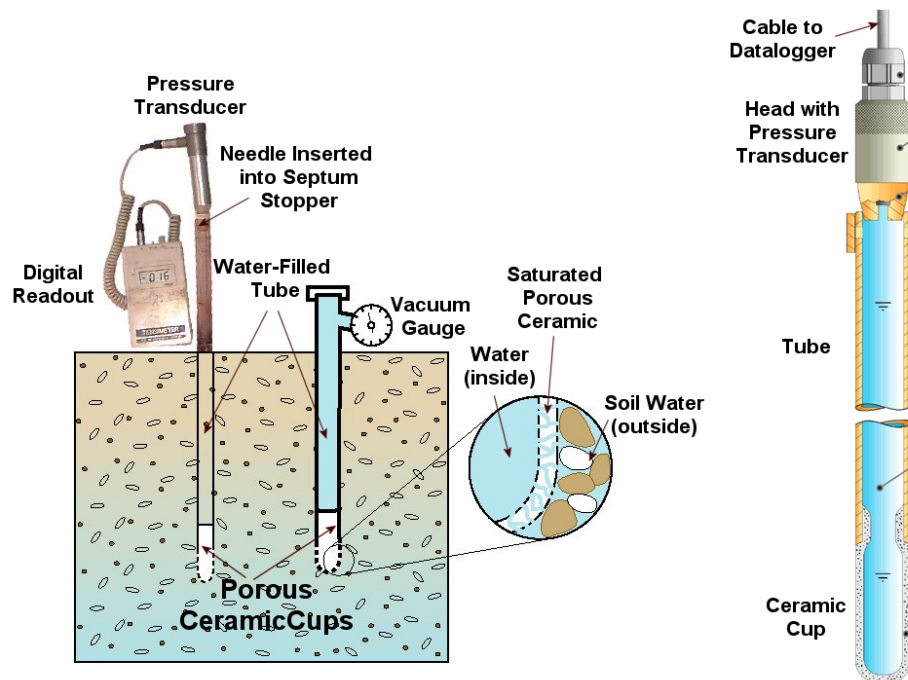


Fig.1-6: Illustration of tensiometers for matric potential measurement using vacuum gauges and electronic pressure transducers.

The vertical distance from the gauge plane to the cup must be added to the matric potential measured by the gauge, ψ_{gauge} , expressed as a negative quantity, in order to obtain the matric potential at the depth of the cup. This accounts for the positive head exerted by the overlying tensiometer water column at the depth of the ceramic cup. Note that using the difference in vertical elevation is appropriate only when potentials are expressed per unit of weight. Electronic sensors called *pressure transducers* often replace the mechanical vacuum gauges. The transducers convert mechanical pressure into an electric signal which can be more easily and more precisely measured. In practice, pressure transducers can provide more accurate readings than other gauges, and in combination with data logging equipment are able to supply continuous measurements of matric potential. The tensiometer range is limited to suction values (negative of the matric potential) of less than 100 kPa, i.e., 1 bar or 10 m head of water. Therefore other means are needed for matric potential measurement under drier conditions.

The limitations of most sensor pairing techniques stem from: (i) differences in the soil volumes sampled by each sensor, e.g. large volume averaging by a neutron probe vs. a small volume sensed by heat dissipation sensor or psychrometer; (ii) while many *in-situ* water content measurement methods are instantaneous, matric potential sensors require time for equilibrium; hence the two measurements may not be indicative of the same wetness level; and (iii) limited ranges and deteriorating accuracy of different sensor pairs; this often results in limited overlap in retention information and problems with measurement errors within the range of overlap (Or and Wraith, 1999a,b).

A summary of the methods available for matric potential measurement and their range of application is presented in Fig.1-7, and are discussed in Or and Wraith (1999a). Note that most of the available techniques have a limited range of overlap or do not overlap at all, and most are laboratory methods not suitable for field applications.

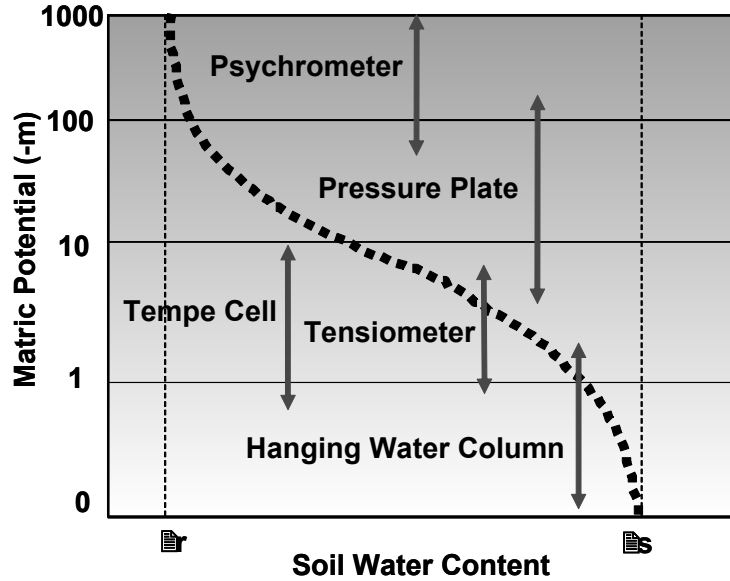


Fig.1-7: A summary of SWC measurement methods for various matric potential ranges.

Fitting Parametric SWC Expressions to Measured Data

Measuring a SWC is laborious and time consuming. Measured θ - ψ pairs are often fragmentary, and usually constitute relatively few measurements over the wetness range of interest. For modelling and analysis purposes and for characterization and comparison between different soils and scenarios it is therefore beneficial to represent the SWC in a continuous and parametric form. A parametric expression of a SWC model should: (i) contain as few parameters as possible to simplify its estimation; and (ii) describe the behaviour of the SWC at the limits, wet and dry ends, while closely fitting the nonlinear shape of ψ_m - θ_v data.

An effective and commonly used parametric model for relating volumetric water content, θ_v , to the matric potential, ψ_m , was proposed by van Genuchten (1980) and is denoted here as VG:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{1}{1 + (\alpha |\psi_m|)^n} \right]^m \quad (14)$$

where θ_r and θ_s are the residual and saturated water contents, respectively, and α , n , and m are parameters directly dependent on the shape of the $\theta(\psi)$ curve. Considerable simplification is gained by assuming that $m=1-1/n$. Thus the parameters required for estimation of the model are θ_r , θ_s , α , and n . θ_s is usually known and is easy to obtain experimentally with good accuracy, leaving only three unknown parameters (θ_r , α and n) to be estimated from the experimental data. Note that θ_r may be taken as $\theta_{-1.5 \text{ MPa}}$, $\theta_{\text{air dry}}$, or a similar value, though it is often advantageous to use it as a fitting parameter.

Another well known parametric model was proposed by Brooks and Corey (1964) and is denoted as BC:

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[\frac{\psi_b}{\psi_m} \right]^\lambda \quad \psi_m > \psi_b$$

$$\Theta = 1 \quad \psi_m \leq \psi_b \quad (15)$$

where ψ_b is a parameter related to the soil matric potential at air entry (b represents "bubbling pressure"), and λ is related to the soil pore size distribution. Matric potentials are expressed as positive quantities, i.e. in absolute values, in both the VG and BC parametric expressions.

Estimation of VG or BC parameters from experimental data requires: (i) sufficient data points, at least 5 to 8 ψ_m - θ_v pairs; and (ii) a program for performing non-linear regression. Recent versions of many computer spreadsheet software programs provide relatively simple and effective mechanisms to perform nonlinear regression. Details of the computational steps required for fitting a SWC to experimental data using commercially-available computer spreadsheet software are given in Wraith and Or (1998). In addition, computer programs for estimation of specific models are also available, e.g., RETC code (van Genuchten et al., 1991).

Fig.1-8 depicts fitted parametric models of van Genuchten (VG) and Brooks and Corey (BC) to LCV silt loam SWC data measured by Or et al. (1991). The resulting best-fit parameters for the VG model are: $\alpha=0.417 \text{ m}^{-1}$; $n=1.75$; $\theta_s=0.513 \text{ m}^3/\text{m}^3$; and $\theta_r=0.05 \text{ m}^3/\text{m}^3$, with coefficient of determination $r^2=0.99$. For the BC model the best parameters are: $\lambda=0.54$; $\psi_b=1.48 \text{ m}$; $\theta_s=0.513 \text{ m}^3/\text{m}^3$; and $\theta_r=0.03 \text{ m}^3/\text{m}^3$ (with $r^2=0.98$). Note the main difference between the VG and the BC model fits is in the discontinuity at $\psi=\psi_b$.

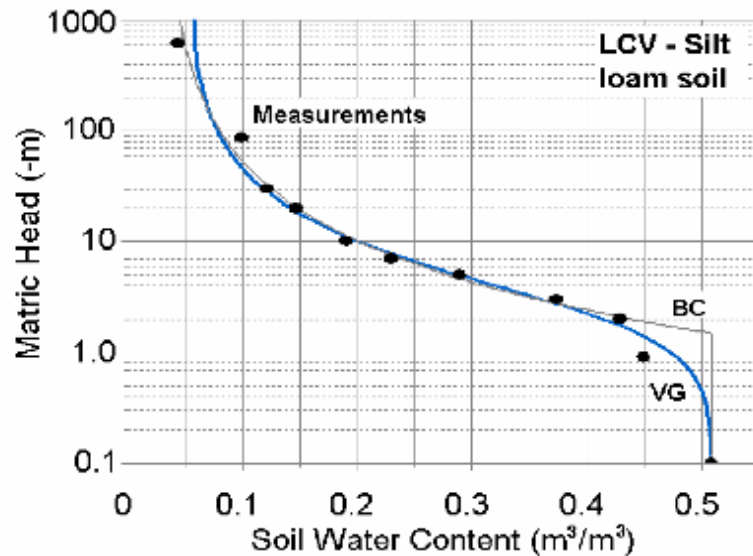


Fig.1-8: VG and BC parametric models fitted to measured silt loam SWC data from Owens Valley, CA.

Key steps in fitting VG model to experimental SWC data using Excel are:

- (1) Enter the experimental data in two columns corresponding to θ_v and ψ_m .
- (2) Establish a cell for each fitting parameter (θ_r , θ_s , α , n), and assign an initial value estimate to each. Note that reasonable initial estimates for all variables may be critical for proper convergence of nonlinear models. That is to say, if your estimates are not reasonably near their true values, the fitting algorithm may converge on a local rather than the true global minimum, or even fail to converge on a solution at all. Consulting the literature for reasonable initial estimates may be appropriate in some cases.
- (3) Write the desired prediction model (i.e. equation) in a third column. Note that Eq.(14) may be stated in terms of θ as:

$$\theta = \theta_r + (\theta_s - \theta_r) \left[\frac{1}{1 + (\alpha |h|)^n} \right]^m \quad (16)$$

and in terms of h as:

$$h = \frac{\left[\left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{-\frac{1}{m}} - 1 \right]^{\frac{1}{n}}}{\alpha} \quad (17)$$

Refer to the pre-assigned cells containing your initial guesses for the fitting parameters where appropriate in the equation. This column will thus contain predicted θ_v values ($\theta_{v \text{ model}}$) for each measured value of ψ_m .

- (4) Form in a fourth column a deviate (or error) squared between θ_v and $\theta_{v \text{ model}}$, i.e. $(\theta_v - \theta_{v \text{ model}})^2$.
- (5) Establish a cell containing the *sum of squared deviations* (errors) between measured and predicted values.
- (6) Apply the nonlinear solver (Solver in the Tools menu for Excel; Optimizer under the Tools menu for Quattro Pro) to the problem by *minimizing the sum of squared errors (SSE) cell using variable cells as defined in Step 2*. You should include the following constraints: $0 \leq m \leq 1$, and $\theta_r \geq 0$.
- (7) Compute the *variance of measured θ_v* (a built-in spreadsheet function). The coefficient of determination (r^2) for the curve fit may then be calculated using:

$$r^2 = 1 - (\text{sum of squared errors}) / (\# \text{ of data points} \times \text{variance of measured } \theta_v).$$
- (8) Record the resulting "best fit" values of the variable cells for subsequent use.

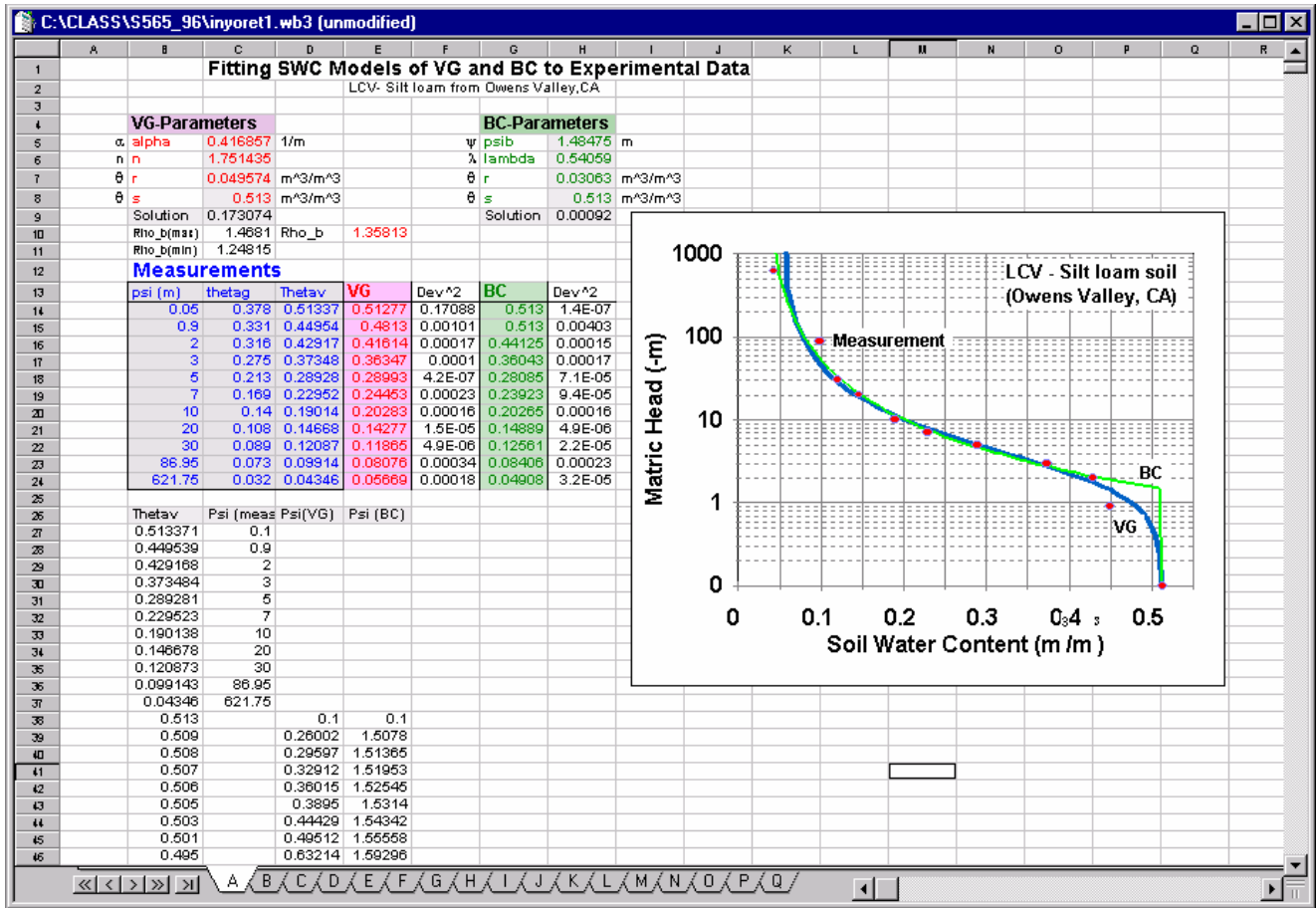


Fig.1-9: A sample worksheet for fitting VG and BC expressions to SWC experimental data.

Procedures

Each group will perform experiments for a single pre-assigned soil type as outlined below.

Tempe Cells for Matric Potential (ψ_m) Range of 0 to -10m

- 1.) Prepare two Tempe cells (duplicates of the same soil type); weigh all its components, including a **saturated** ceramic plate (Fig.1), and record the results.
- 2.) Assemble the bottom part of the Tempe cell by placing the o-rings into the appropriate grooves, and inserting the saturated ceramic plate.
- 3.) Insert an empty brass-ring into the bottom part; pour known amounts of oven-dried soil into the ring and tap gently on the brass ring; fill the ring to about 2-3 mm from its top (Fig.2); clean the soil from the edge of the ring.
- 4.) Attach a Mariotte tower to the bottom of the Tempe cell using Tygon tubing, and allow saturation from the bottom; maintain a hydraulic head that is slightly below (2 mm) the top of the sample. Saturate the sample until a glossy water film is visible on the sample surface.

- 5.) Attach the top portion of the Tempe cell and weigh the cell including the saturated sample.
- 6.) Connect the saturated Tempe cell to the pressure manifold and attach an outflow collector to the bottom (Fig.3) (we will try to keep track of the outflow to double-check changes in water content).
- 7.) We will apply 3 pressure steps of 1, 4, and 8 meters of H₂O. After each pressure step we will disconnect the Tempe cell from the pressure manifold and determine the weight. To double check we will also determine the weight of the outflow collected (please keep track of the amounts!).
- 8.) The schedule for pressure changes is as follows:
 - We will start applying a pressure of 1m during the laboratory on Tuesday
 - On Wednesday between 2 and 3 pm we will increase the pressure to 4 m
 - On Thursday between 2 and 3 pm (during lab session) we will increase the pressure to 8 m
 - On Friday at 2 PM (one hour before the ENVE 400 seminar) pressure will be disconnected, weigh and disassemble the cells; brass rings containing the soil should be placed in a drying oven to determine the water content and the bulk density of the soil.

At least one member of each group should be present on, Wednesday and Friday to weigh the Tempe cells (and for other data collection duties).



Fig.1: Tempe cell parts



Fig.2: Assembled Tempe cell with sample



Fig.3: Tempe cells connected to pressure lines and outflow flasks.

Pressure Plate Apparatus for Matric Potential (ψ_m) Range of -10 to -50m

- 1.) Arrange four plastic retaining rings on the saturated pressure plate in the pressure chamber (Fig.4). Each group will perform the measurements for two samples of each soil.
- 2.) Use a spoon to pour oven dry and sieved soil into the retaining rings. Create a small pile within the ring (Fig.4)
- 3.) When all samples are in place, we will raise the water level on the pressure plate slowly to cover the plate's surface and to saturate the soil samples from the bottom (in general samples should be left overnight for saturation, however due to time limitations we will allow a saturation time of a few minutes).
- 4.) After saturation is complete, we will connect the outflow tube, and seal the chamber by fastening the cover bolts.
- 5.) A single pressure step of 25 m of water (2.45 bars or 0.245 MPa) will be applied.
- 6.) On Friday we will remove the samples from the pressure chambers. **Make sure that the pressure supply line is closed, and the pressure is released before opening the chambers!**
- 7.) We will transfer the samples from the pressure plate to pre-weighed drying dishes, weigh the wet samples, and place the drying dish in to the oven to determine the gravimetric water content.



Fig.4: Pressure chamber with saturated ceramic plate and retaining rings.

Dewpoint PotentiaMeter for Matric Potential (ψ_m) Range from -50 to -150m

- 1.) This measurement will be explained and assisted by the instructor.
- 2.) We will use pre-wetted soil samples to prescribed gravimetric water contents of approximately: 0.02, 0.04, 0.08, and 0.1, [g/g] (moist soil samples were stored in ziplock bags for more than 48 hrs to equilibrate).
- 3.) The instructor will perform the Dewpoint PotentiaMeter readings and provide four values of matric potential for each soil (one for each water content)

- 4.) Students will determine the gravimetric water content in the remainder of the samples (i.e., the portion not used in the Potentiometer).
- 5.) Use the bulk densities determined during the first laboratory session to convert gravimetric to volumetric water contents.

The user manual for the WP4 Dewpoint Potentiometer is posted on the course website for interested students.



Fig.6: WP4 Dewpoint Potentiometer.

In-Situ SWC Determination from Tensiometric and TDR Measurements

- 1.) Identify the column, soil type (similar to previous section), TDR probes, Tensiometers, etc.; pack the column while keeping track of the weights to estimate bulk density.
- 2.) Based on an estimate of θ_s for your soil type, and assuming that $\theta_r=0.02$, determine the amount of water needed to fill 1/3 of the free pores in the soil contained in the column (to avoid excessive drainage and allow for redistribution).
- 3.) Install two three-rod TDR probes horizontally through pre-drilled holes in the column (each probe is 0.1 m long) – the vertical distance between the probes is 120 mm.
- 4.) Install two vertical tensiometers through the top surface and ensure that center of the ceramic cups are aligned with the two TDR probes (measure the distance from the soil surface and from the gauge to the cup).
- 5.) The tensiometers will be equipped with pressure transducers connected to a datalogger to provide an accurate and continuous measurement (in case of complications, we will use either a Tensimeter or a mechanical gauge).
- 6.) Record the tensiometers response during the first 10 min.
- 7.) Apply the water carefully (avoid disturbance of soil surface) and continue recording the tensiometers response vs. time since water application.
- 8.) Direct an air fan toward the soil surface to enhance evaporation.
- 9.) Hook the TDR probes to an SDM-50 multiplexer controlled by WinTDR program through a laptop (instructor will assist with TDR system initial setup). Be prepared to take manual measurements in case of complications. Record measurements at 15 min intervals. If manual measurements were made, record the positions of the reflection points vs. time; convert to volumetric water contents.
- 10.) Continue sampling at least once a day for 3-4 days (following sampling schedule of other elements above).

Lab Report (Due Tue 03/09/04)

- 1.) Follow the guidelines in the syllabus
- 2.) Write a short introduction and a briefly discuss SWC curves and field and laboratory methods for their measurement.
- 3.) Report on a worksheet all measurements of soil water content, bulk density and matric potential (show raw data and final results).
- 4.) Combine and plot your $\psi_m-\theta_v$ data obtained by the four methods. Use the format of θ_v on the x-axis in units of (m^3/m^3) and ψ_m in units of m of water (use log scale for ψ_m). Convert gravimetric water contents to volumetric water contents using the bulk densities obtained in the first laboratory.
- 5.) Fit the van Genuchten parametric SWC model to the data using the procedure outlined in the handout. Include the fitted curve on the plot and report the parameters.
- 6.) Discuss (briefly) advantages, disadvantages, and possible errors associated with each method. Discuss why is it possible to use disturbed soil samples to determine the $\psi_m-\theta_v$ relationships at relatively high values of suction (or low matric potential range).