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Standard Guide for
Measuring Matric Potential in Vadose Zone Using Tensiometers[1]

This standard is issued under the fixed designation D3404; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers the measurement of matric potential in the vadose zone using tensiometers. The theoretical and practical considerations pertaining to successful onsite use of commercial and fabricated tensiometers are described. Measurement theory and onsite objectives are used to develop guidelines for tensiometer selection, installation, and operation.

1.2 *Units*—The values stated in SI units are to be regarded as the standard. The inch-pound units given in parentheses are for information only.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use. The use of a mercury manometer has inherent safety concerns regarding the handling of and potential exposure to mercury. Mercury metal vapor poisoning has long been recognized as a hazard. When using equipment containing or requiring the use of mercury, take all precautions and care to avoid the escape of mercury vapor or the spillage of mercury. Maximum limits for mercury concentrations in industrial atmospheres are set by governmental agencies. These limits are usually based upon recommendations made by the American Conference of Governmental Industrial Hygienists*. It is possible for the concentration of mercury vapors accompanying spills from broken thermometers, barometers, and other instruments using mercury to exceed these limits. Mercury, being a heavy liquid with high surface tension, readily disperses into small droplets after spills, lodging in cracks and crevices. Resultant increased surface area of the mercury due to this dispersion promotes higher mercury concentrations in the surrounding air. Mercury vapor concentrations are readily measured using commercially available instrumentation. To monitor environmental hazards it is advisable to make periodic checks for mercury content at locations where mercury is exposed to the atmosphere. Use a spill kit for clean-up whenever spillage occurs. After spills and clean-up, make thorough checks for mercury vapor concentrations in the atmosphere. *In 1993, this Conference had headquarters located in Building D-7 at 6500 Glenway Drive, Cincinnati, Ohio 45211.*

1.4 *This guide offers an organized collection of information or a series of options and does not recommend a specific course of action. This document cannot replace education or experience and should be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This ASTM standard is not intended to represent or replace the standard of care by which the adequacy of a given professional service must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word" Standard" in the title of this document means only that the document has been approved through the ASTM consensus process.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]
D653 Terminology Relating to Soil, Rock, and Contained Fluids

3. Terminology

3.1 For definitions of common technical terms in this standard, refer to Terminology D653.

3.2 *Definitions of Terms Specific to This Standard:*
3.2.1 *accuracy of measurement*—the difference between the value of the measurement and the true value.

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[1] This guide is under the jurisdiction of ASTM Committee D18 on Soil and Rock and is the direct responsibility of Subcommittee D18.21 on Groundwater and Vadose Zone Investigations.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

3.2.2 *hysteresis*—that part of inaccuracy attributable to the tendency of a measurement device to lag in its response to environmental ~~changes. Parameters~~changes; parameters affecting pressure-sensor hysteresis are temperature and measured pressure.

3.2.3 *precision (repeatability)*—the variability among numerous measurements of the same quantity.

3.2.4 *resolution*—the smallest division of the scale used for a measurement, and it is a factor in determining precision and accuracy.

4. Summary of Guide

4.1 The measurement of matric potential in the vadose zone can be accomplished using tensiometers that create a saturated hydraulic link between the soil water and a pressure sensor. A variety of commercial and fabricated tensiometers are commonly used. A saturated porous ceramic material that forms an interface between the soil water and bulk water inside the instrument is available in many shapes, sizes, and pore diameters. A ~~gage,~~gauge, manometer, or electronic pressure transducer is connected to the porous material with small- or large-diameter tubing. Selection of these components allows the user to optimize one or more characteristics, such as accuracy, versatility, response time, durability, maintenance, extent of data collection, and cost.

5. Significance and Use

5.1 Movement of water in the unsaturated zone is of considerable interest in studies of hazardous-waste sites (**1, 2, 3, 4**)[3]; recharge studies (**5, 6**); irrigation management (**7, 8, 9**); and civil-engineering projects (**10, 11**). Matric-potential data alone can be used to determine direction of flow (**11**) and, in some cases, quantity of water flux can be determined using multiple tensiometer installations. In theory, this technique can be applied to almost any unsaturated-flow situation whether it is recharge, discharge, lateral flow, or combinations of these situations.

5.2 If the moisture-characteristic curve is known for a soil, matric-potential data can be used to determine the approximate water content of the soil (**10**). The standard tensiometer is used to measure matric potential between the values of 0 and -867 cm of water; this range includes most values of saturation for many soils (**12**).

5.3 Tensiometers directly and effectively measure soil-water tension, but they require care and attention to detail. In particular, installation needs to establish a continuous hydraulic connection between the porous material and soil, and minimal disturbance of the natural infiltration pattern are necessary for successful installation. Avoidance of errors caused by air invasion, nonequilibrium of the instrument, or pressure-sensor inaccuracy will produce reliable values of matric potential.

5.4 Special tensiometer designs have extended the normal capabilities of tensiometers, allowing measurement in cold or remote areas, measurement of matric potential as low as -153 m of water (-15 bars), measurement at depths as deep as 6 m (recorded at land ~~surface), and~~ surface) for conventional tensiometers, depths up to 200 m and greater with advanced and portable versions (**13,14**), and automatic measurement using as many as 22 tensiometers connected to a single pressure transducer, but these require a substantial investment of effort and money.

5.5 Pressure sensors commonly used in tensiometers include vacuum ~~gages,~~gauges, mercury manometers, and pressure transducers. Only tensiometers equipped with pressure transducers allow for the automated collection of large quantities of data. However, the user needs to be aware of the pressure-transducer specifications, particularly temperature sensitivity and long-term drift. Onsite measurement of known zero and "full-scale" readings probably is the best calibration procedure; however, onsite temperature measurement or periodic recalibration in the laboratory may be sufficient.

6. Measurement Theory

6.1 In the absence of osmotic effects, unsaturated flow obeys the same laws that govern saturated flow: Darcy's Law and the Equation of Continuity, that were combined as the Richards' Equation (**13**15). Baver et al. (**14**16) presents Darcy's Law for unsaturated flow as follows:

$$q = -K\nabla(\psi + Z) \tag{1}$$

where:

q = the specific flow, $\left[\frac{L}{T}\right]$,

K = the unsaturated hydraulic conductivity, $\left[\frac{L}{T}\right]$,

ψ = the matric potential of the soil water at a point, [L],

Z = the elevation at the same point, relative to some datum, [L], and

∇ = the gradient operator, [L^{-1}].

The sum of $\psi + Z$ commonly is referred to as the hydraulic head.

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[3] The boldface numbers in parentheses refer to a list of references at the end of this standard.

6.2 Unsaturated hydraulic conductivity, K, can be expressed as a function of either matric potential, ψ, or water content, $\theta[L^3$ of water/L^3 of soil], although both functions are affected by hysteresis (**5**). If the wetting and drying limbs of the $K(\psi)$ function are known for a soil, time series of onsite matric-potential profiles can be used to determine which limb is more appropriate to describe the onsite $K(\psi)$, the corresponding values of the hydraulic-head gradient, and an estimate of flux using Darcy's Law. If, instead, K is known as a function of θ, onsite moisture-content profiles (obtained, for example, from neutron-scattering methods) can be used to estimated K, and combined with matric-potential data to estimate flux. In either case, the accuracy of the flux estimate needs to be assessed carefully. For many porous media, $\frac{dK}{d\psi}$ and $\frac{dK}{d\theta}$ are large, within certain ranges of ψ or θ, making estimates of K particularly sensitive to onsite-measurement errors of ψ or θ. (Onsite-measurement errors of ψ also have direct effect on $\nabla(\psi + Z)$ in Darcy's Law). Other sources of error in flux estimates can result from inaccurate data used to establish the $K(\psi)$ or $K(\theta)$ functions (accurate measurement of very small permeability values is particularly difficult) (**1517**); use of an analytical expression for $K(\psi)$ or $K(\theta)$ that facilitates computer simulation, but only approximates the measured data; an insufficient density of onsite measurements to define adequately the θ or ψ profile, which can be markedly nonlinear; onsite soil parameters that are different from those used to establish $K(\psi)$ or $K(\theta)$; and invalid assumptions about the state of onsite hysteresis. Despite the possibility of large errors, certain flow situations occur where these errors are minimized and fairly accurate estimates of flux can be obtained (**6, 1618**) . The method has a sound theoretical basis and refinement of the theory to match measured data markedly would improve reliability of the estimates.

6.3 The concept of fluid tension refers to the difference between standard atmospheric pressure and the absolute fluid pressure. Values of tension and pressure are related as follows:

$$T_F = P_{AT} - P_F \tag{2}$$

where:

T_F = the tension of an elemental volume of fluid, $\left[\dfrac{M}{LT^2}\right]$,

P_{AT} = the absolute pressure of the standard atmosphere, $\left[\dfrac{M}{LT^2}\right]$, and

P_F = the absolute pressure of the same elemental volume or fluid $\left[\dfrac{M}{LT^2}\right]$.

Soil-water tension (or soil-moisture tension) similarly is equal to the difference between soil-gas pressure and soil-water pressure. Thus:

$$T_W + P_G = P_W \tag{3}$$

where:

T_W = the tension of an elemental volume of soil water, $\left[\dfrac{M}{LT^2}\right]$,

P_G = the absolute pressure of the surrounding soil gas, $\left[\dfrac{M}{LT^2}\right]$, and

P_W = the absolute pressure of the same elemental volume of soil water, $\left[\dfrac{M}{LT^2}\right]$.

In this guide, for simplicity, soil-gas pressure is assumed to be equal to 1 atm, except as noted. Various units are used to express tension or pressure of soil water, and are related to each other by the equation:

$$1.000 \text{ bar} = 100.0 \text{ kPa} = 0.9869 \text{ atm} = \tag{4}$$

$$1020 \text{ cm of water at } 4°C =$$

$$1020 \text{ g per cm}^2 \text{ in a standard}$$

$$\text{gravitational field.}$$

A standard gravitational field is assumed in this guide; thus, centimetres of water at 4°C are used interchangeably with grams per square centimetre.

6.4 The negative of soil-water tension is known formally as matric potential. The matric potential of water in an unsaturated soil arises from the attraction of the soil-particle surfaces for water molecules (adhesion), the attraction of water molecules for each other (cohesion), and the unbalanced forces across the air-water interface. The unbalanced forces result in the concave water films typically found in the interstices between soil particles. Baver et al. (~~14~~16) present a thorough discussion of matric potential and the forces involved.

6.5 The tensiometer, formally named by Richards and Gardner (~~17~~19), has undergone many modifications for use in specific problems (1, 11, ~~18-20-30~~32). However, the basic components have remained unchanged. A tensiometer comprises a porous surface (usually a ceramic cup) connected to a pressure sensor by a water-filled conduit. The porous cup, buried in a soil, transmits the soil-water pressure to a manometer, a vacuum ~~gage,~~gauge, or an electronic-pressure transducer (referred to in this guide as a pressure transducer). During normal operation, the saturated pores of the cup prevent bulk movement of soil gas into the cup.

6.6 An expanded cross-sectional view of the interface between a porous cup and soil is shown in Fig. 1. Water held by the soil
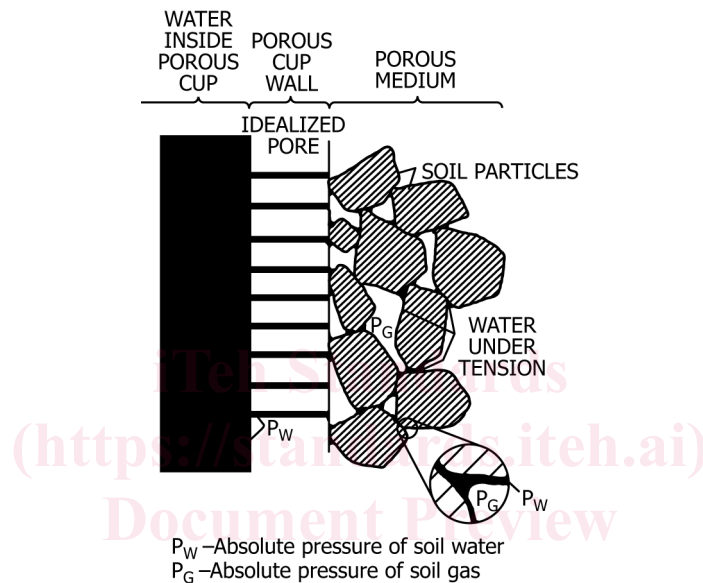

P_W –Absolute pressure of soil water
P_G –Absolute pressure of soil gas

FIG. 1 Enlarged Cross Section of Porous Cup-Porous Medium Interface

particles is under tension; absolute pressure of the soil water, P_W, is less than atmospheric. This pressure is transmitted through the saturated pores of the cup to the water inside the cup. Conventional fluid statics relates the pressure in the cup to the reading obtained at the manometer, vacuum ~~gage,~~gauge, or pressure transducer.

6.6.1 In the case of a mercury manometer (see Fig. 2(a)):

$$T_W = P_A - P_W = (\rho_{Hg} - \rho_{H_2O})r - \rho_{H_2O}(h+d) \tag{5}$$

where:

T_W = the soil-water tension relative to atmospheric pressure, in centimetres of water at 4°C,
P_A = the atmospheric pressure, in centimetres of water at 4°C,
P_W = the average pressure in the porous cup and soil, in centimetres of water at 4°C,
ρ_{Hg} = the average density of the mercury column, in grams per cubic centimetre,
~~ρ_{H_2O} = the average density of the water column, in grams per cubic centimetre,~~
ρ_{water} = the average density of the water column, in grams per cubic centimetre,
r = the reading, or height of mercury column above the mercury-reservoir surface, in centimetres,
h = the height of the mercury-reservoir surface above land surface, in centimetres, and
d = the depth of the center of the cup below land surface, in centimetres.

6.7 Although the density of mercury and water both vary about 1 % between 0 and 45°C, Eq 8 commonly is used with ρ_{Hg} and $\rho_{\text{~~H~~water~~₂O~~}}$ constant.

6.7.1 Using ρ_{Hg} = 13.54 and $\rho_{\text{~~H~~water~~₂O~~}}$ = 0.995 (the median values for this temperature range) yields about a 0.25 % error (1.5 cm ~~H~~of~~₂O)~~ water) at 45°C, for Tw ≈ 520 cm ~~H~~of~~₂O.~~ water. This small, but needless, error can be removed by using the following density functions:

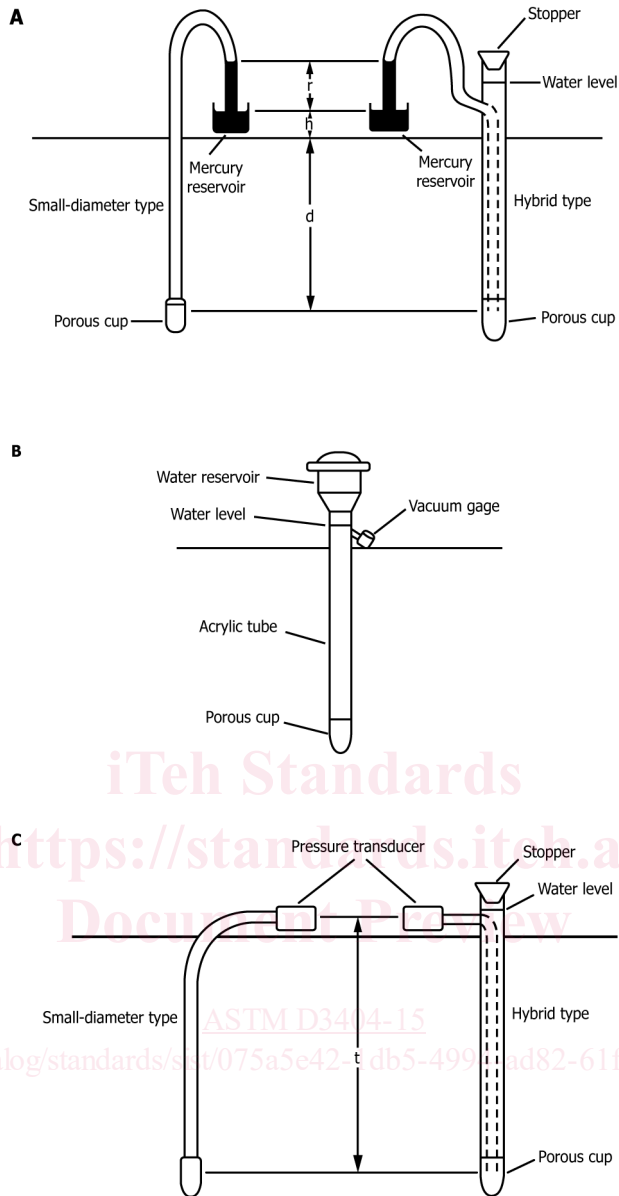$$\rho_{Hg} = 13.595 - 2.458 \times 10^{-3}(T) \tag{6}$$

and

FIG. 2 Three Common Types of Tensiometers: (a) Manometer; (b) Vacuum ~~Gage;~~Gauge; and (c) Pressure Transducer

$$\rho_{H_2O} = 0.9997 + 4.879 \times 10^{-5} (T) - 5.909 \times 10^{-6} (T)^2 \qquad (7)$$

$$\rho_{water} = 0.9997 + 4.879 \times 10^{-5} (T) - 5.909 \times 10^{-6} (T)^2 \qquad (7)$$

where: ρ_{Hg} and $\rho_{\text{~~H~~water}_{~~2~~}O}$ are as defined above, and
T = average temperature of the column, in °C.

6.7.2 Average temperature of the buried segment of water column can be estimated with a thermocouple or thermistor in contact with the tubing, buried at about 45 % of the depth of the porous cup. Air temperature is an adequate estimate for exposed segments.

6.8 Most vacuum ~~gages~~gauges used with tensiometers are graduated in bars (and centibars) and have an adjustable zero-reading. The zero adjustment is used to offset the effects of altitude, the height of the ~~gage~~gauge above the porous cup (see Fig. 3(*b*)), and changes in the internal characteristics of the ~~gage~~gauge with time. The adjustment is set by filling the tensiometer with water and then setting the ~~gage~~gauge to zero while immersing the porous cup to its midpoint in a container of water. This setting is done at the altitude at which the tensiometer will be used and it needs to be repeated periodically after installation either by removing the tensiometer from the soil or by unscrewing the ~~gage~~gauge and measuring a tension equal to that used in the original calibration. The ~~gage~~gauge then reads directly the tension in the porous cup. Use of a vacuum ~~gage~~gauge without an adjustable zero reading could result in inaccurate measurements because the zero reading could become negative and, therefore, would be indeterminate.
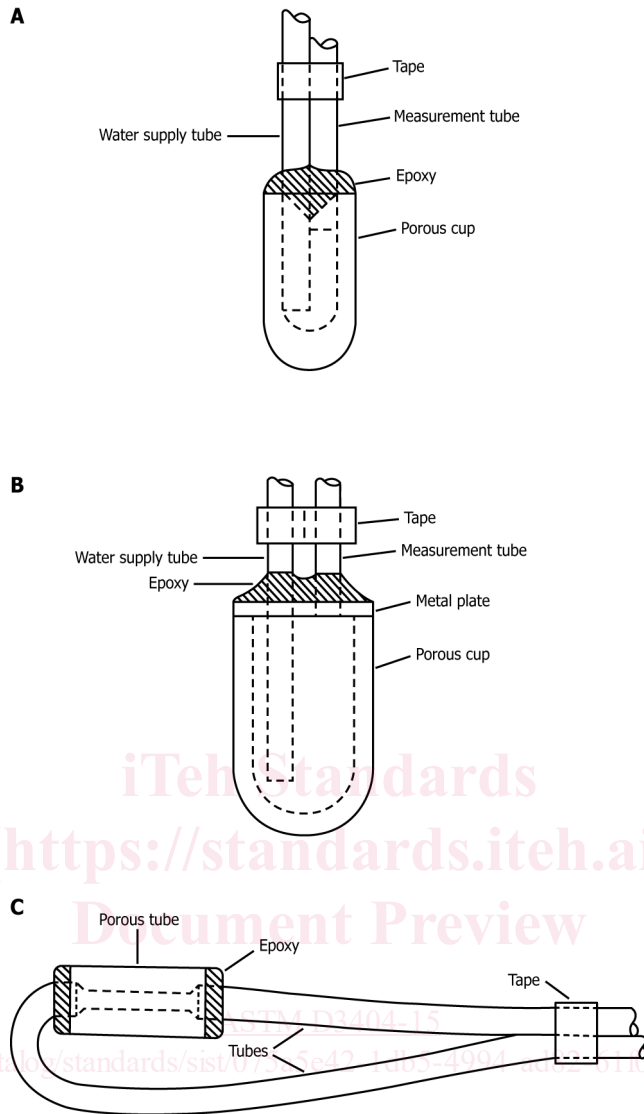
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FIG. 3 Porous-Cup and Tube Designs

6.9 Pressure transducers convert pressure, or pressure difference, into a voltage (or current) signal. The pressure transducer can be connected remotely to the porous cup with tubing (~~21~~23, ~~23~~25), attached directly to the cup (~~18~~20, ~~31~~33), or transported between sites (~~23~~25). An absolute pressure transducer measures the absolute pressure (P_P) in its port. A ~~gage~~gauge pressure transducer measures the difference between ambient-atmospheric pressure (P_A) and the pressure in its port (P_P), known as ~~gage~~gauge pressure. When $P_P < P_A$, ~~gage~~gauge pressure is identical to tension. A differential pressure transducer measures the difference between two pressures; one in each of its two ports. When used with tensiometers, the second port usually is connected to the atmosphere; the unit is used as a ~~gage~~gauge pressure transducer and it measures tension.

6.10 A calibration equation supplied by the manufacturer, or determined by the user, is used to convert the measured signal into pressure or tension at the pressure-transducer port. The tension in the porous cup and soil is then (see Fig. 3(c)):

$$T_W = T_P - t\left(\rho_{H_2O}\right) \tag{8}$$

$$T_W = T_P - t\left(\rho_{water}\right) \tag{8}$$

where:

T_W = the average tension in the porous cup and soil, in centimetres of water at 4°C,
T_P = the tension in the pressure-transducer port, in centimetres of water at 4°C,
t = the difference in elevation between the pressure-transducer port and the center of the porous cup, in centimetres, and
~~ρ_{H_2O}~~ = ~~the average density of the water column connecting the porous cup and transducer, in grams per cubic centimetre.~~
ρ_{water} = the average density of the water column connecting the porous cup and transducer, in grams per cubic centimetre.