

## TENSIOMETRY

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### Introduction

The practical application of equilibrium and nonequilibrium concepts to the hydrostatics and hydrodynamics of soil water in laboratory and field environments depends on the ability to measure relevant potentials. In unsaturated soils, the matric and gravitational potentials are usually regarded as the hydraulically important energy components. A tensiometer is a device used to measure the matric potential,  $\psi_m$ , the component of the soil water chemical potential that is directly dependent on water content. When the local soil gas phase pressure differs from that of the reference pressure (usually taken as the local atmospheric pressure), the tensiometer reading also includes this difference as an additional air pressure potential. Thus, the tensiometer most generally equilibrates to the sum of the matric and air pressure (pneumatic) potentials, also referred to as the tensiometer potential. In addition, tensiometers can be sensitive to shrinking and swell of soils. For simplicity, this summary will be restricted to conditions where the soil gas phase is in equilibrium with the atmosphere, and soil volume changes are negligible, such that the tensiometer equilibrates simply with the soil matric potential. In the following sections basic features of tensiometers, their equilibrium conditions, response time, and operational range are summarized. This survey concludes with a few design considerations, and a list of some suppliers of tensiometers.

The basic components of a tensiometer consist of a porous tip or cup, an internal cavity, and a device to measure pressure within the cavity (Figure 1). The water-saturated porous boundary (the tensiometer tip or cup) is placed in contact with soil. This permits exchange of soil water between the region of interest and the tensiometer cavity until equilibrium is reached. Thus, the measurement of matric (or capillary) potential is generally achieved through determining the pressure of a fluid phase within the tensiometer, after equilibrium with the surrounding soil has been established. If the water table rises up to or above the tip, the tensiometer provides a measurement of the local pressure potential rather than the matric potential. Because most tensiometers rely on measuring the pressure of liquid water inside the tensiometer body, the lowest attainable equilibrium reading is imposed by the vapor pressure of water. Although this suggests that the lower operational limit ranges from -100 to -95 kPa for temperatures ranging from 5° to 35°C, a practical lower limit of about -85 kPa is commonly encountered because of exsolution of gases (air). The lower operating limit should be taken into account in selecting the porous tensiometer tip (discussed in more detail later). Hydrophilic ceramics are most commonly used, but water-wettable porous glass, stainless steel, plastic, cloth, and even paper are used for tensiometer tips in various applications. The air-entry value of the porous tip is the gauge pressure at which the air phase displaces water-filled pores. Thus, when the matric potential decreases (becomes more negative) such that its magnitude is larger than the air-entry value, air leaks in through the tip,

causing the tensiometer to fail. Ceramics with air-entry values of about -100 kPa are typically used for tensiometer tips in field applications. More permeable ceramics with lower magnitude air-entry suctions (e.g. -50 to -5 kPa) are used in some laboratory applications.

<Figure 1 near here>

The original tensiometers, developed in the early 20<sup>th</sup> century, consisted of a water-filled porous interface connected to a manometer. Since introduction of these early instruments, a wide variety of tensiometer designs have been developed. In field applications, tensiometers are used for irrigation scheduling, characterization of flow in soil profiles and deeper unsaturated sediments, and monitoring of contaminated soils. In the laboratory, tensiometers are used in soil physics, agricultural, and vadose zone hydrologic research. Basic characteristics common to all tensiometer applications are reviewed in the following sections.

### **Equilibrium**

By measuring the pressure of a fluid phase within a tensiometer, a measurement of the soil matric potential is obtained. The reliability of this measurement depends on establishing local equilibrium between the tensiometer and the soil, and on the condition that the matric potential is within the instruments operational range, criteria that are discussed later. Equilibrium between the soil water and tensiometer can be viewed mechanically as a balance between capillary and adsorptive forces retaining water in the soil on one hand, and the hydrostatic pressure (suction) of water within the tensiometer. More generally, net exchange of soil water between the tensiometer (system) and soil (reservoir) occurs until differences in soil water chemical potential vanish. At this state, the gauge pressure in the tensiometer at the elevation of interest (denoted  $P_1$  in Figure 1) is equal to  $\psi_m$ . When the pressure is recorded at an elevation different from that of the tensiometer tip, a hydrostatic correction is applied. In the example shown in Figure 1,  $\psi_m = P_2 + \rho_w g L$ , where  $\rho_w$  is the density of water, and  $g$  is the acceleration due to gravity. The time necessary to attain such equilibrium is generally determined by hydraulic properties of the soil, the soil-tensiometer contact, and response characteristics of the tensiometer.

### **Response Time**

The time required to attain soil-tensiometer equilibrium depends on two basic factors; the rate of soil water transfer, and the change in tensiometer pressure per unit mass of soil water exchanged. These two factors can be parameterized in terms of the tensiometer-soil conductance and tensiometer gauge sensitivity. The overall conductance is determined by the (saturation-dependent) soil hydraulic conductivity, hydraulic contact between the soil and tensiometer tip, and the conductance of the tensiometer tip. Here, only the strictly tensiometer-dependent factors of tip conductance and gauge sensitivity will be addressed. In order to rapidly obtain a tensiometer reading that accurately reflects the local soil matric potential, it is desirable to maximize both the tip conductance and the gauge sensitivity. As shown below, the product of these two parameters is equal to the inverse of the instrument's response time.

The tensiometer conductance,  $K$ , is a measure of the volumetric rate that water can flow through a tensiometer tip per unit hydraulic potential difference. When the potential difference (outside minus inside of the tensiometer) is expressed in terms of hydraulic head,  $K$  has dimension of  $[L^2 T^{-1}]$ . The preferred maximization of  $K$  in order to shorten tensiometer response times can be achieved through increasing the permeability and bulk area of the porous tip, and decreasing the thickness of the tip. Each of these strategies is subject to constraints. Increasing the permeability of the tip material is achieved by increasing its characteristic pore-size (since permeability scales to the square of pore diameter), and narrowing its pore-size distribution. However, the extent to which the characteristic pore-size can be increased is severely limited by the fact that the air-entry pressure is inversely proportional to pore-size. Thus more permeable tensiometer tips will not permit measurements of lower (more negative) matric potentials. The bulk surface area of the ceramic can be increased in order to provide more area through which soil water is exchanged. This option is limited when spatially resolved measurements of potential distributions are needed, and when constraints are associated with installation (labor and/or disturbance of soil profiles). The final option available for increasing the tensiometer tip conductance involves decreasing the thickness of the porous ceramic or membrane. Compromised mechanical integrity imposes the primary limit to this option. In addition, thinner membranes may require more structural support to minimize flexing in response to pressure changes. This latter effect compromises the tensiometer's sensitivity.

The change in a tensiometer's pressure reading per unit volume ( $V_w$ ) exchange of soil water defines its gauge sensitivity,  $S$ . When the pressure reading is expressed in head ( $h$  [L]) units,  $S$  has dimensions of  $[L^{-2}]$ . Different types of pressure indicators have vastly different gauge sensitivities. Assuming the tensiometer cavity is rigid and completely water-filled, a pressure transducer can provide  $S > 10^9 \text{ m}^{-2}$ . In contrast, a simple water manometer (practical only for low magnitude  $\psi_m$  measurements) has  $S = dh/dV_w = A^{-1}$ , where  $A$  is the cross-sectional area of the manometer tube. A 2 mm inner diameter water manometer thus has a sensitivity of  $3 \times 10^5 \text{ m}^{-2}$ . Improving the sensitivity of manometer-based tensiometry through decreasing  $A$  is limited due to also increasing the uncertainty of the contact angle-dependent capillary rise (water) or capillary depression (mercury). Although the aforementioned values span a very wide range, most mechanical (Bourdon tube vacuum gauge) and electronic pressure transducers used in tensiometry have  $S$  in the range of  $10^7$  to  $10^9 \text{ m}^{-2}$ . It should be noted that because gases are highly compressible, the presence of air within tensiometers decreases  $S$ . The  $S$  associated with a gas cavity of volume  $V$  is equal to  $P(\rho_w g V)^{-1}$ , where  $P$  is the absolute pressure of the gas. Thus, a  $1 \text{ cm}^3$  volume of air inside a tensiometer will allow  $S$  to be no greater than  $10^7 \text{ m}^{-2}$ , even when a much more sensitive pressure transducer is used to obtain that pressure reading.

The tensiometer's response time,  $\tau$ , indicates how rapidly the instrument equilibrates with its environment when the rate of soil water exchange is controlled by the tip conductance (rather than the soil or soil-tensiometer contact). Under such conditions of tensiometer-limited response, the time parameter is related to  $K$  and  $S$  through  $\tau = (KS)^{-1}$ . The rate at

which the tensiometer reading  $R$  relaxes towards its equilibrium value  $R_{eq}$  is then proportional the instantaneously magnitude of disequilibrium,

$$\frac{dR}{dt} = -\frac{(R - R_{eq})}{\tau} \quad [1]$$

In most tensiometers,  $\tau$  is practically constant over the operational range such that  $R_{eq}$  is approached according to

$$\frac{R - R_{eq}}{R_0 - R_{eq}} = e^{-t/\tau} \quad [2]$$

where  $R_0$  is the initial tensiometer reading. Thus  $\tau$  is equal to the time require to diminish the difference between an arbitrary initial reading and the equilibrium reading to  $e^{-1}$  (about 37%) of the original discrepancy. By  $t = 5\tau$ , the tensiometer reading is within 1% of  $R_{eq}$  relative to the original discrepancy. Although tensiometers relying on pressure transducers or vacuum gauges have  $\tau$  values are in the range of fractions of seconds to seconds, much slower responses are obtained in most applications due to low unsaturated hydraulic conductivity of the soil and poor tensiometer-soil hydraulic contact.

### **Range of Applications**

Given the wide variety of environments in which it is desirable to have information on matric potentials, it is worth addressing limitations in ranges of tensiometer applications as well as approaches that have been developed to diminish or circumvent limitations. Here, lower ranges in matric potential, tensiometry in deep unsaturated zones, and temperature-related problems are briefly discussed.

Although water-filled tensiometers have a lower practical limit of about -85 kPa, much lower matric potentials can be measured with osmotic tensiometers. In an osmotic tensiometer, a polymer solution within the tensiometer body equilibrates with soil water through a semipermeable membrane (ideally impervious to the polymer. The polymer solution equilibrates at a positive gauge pressure (in order to compensate for water potential lowering resulting from interactions with the polymer), thereby avoiding negative gauge pressure limitations of conventional tensiometers. Problems arising from high sensitivity to thermal fluctuations and slow leakage of the polymer have severely limited use of osmotic tensiometers, but recent advances may lead to wider interest in this alternative.

Interest in flow through deep unsaturated soils and sediments has grown over the past two decades, and this has necessitated development of deep tensiometry methods for field applications. Use of a conventional field tensiometer with a water-filled column to provide the hydraulic connection between the buried tensiometer tip and the pressure gauge at the soil surface (e.g., Figure 1) permits a decreasing range of matric potential

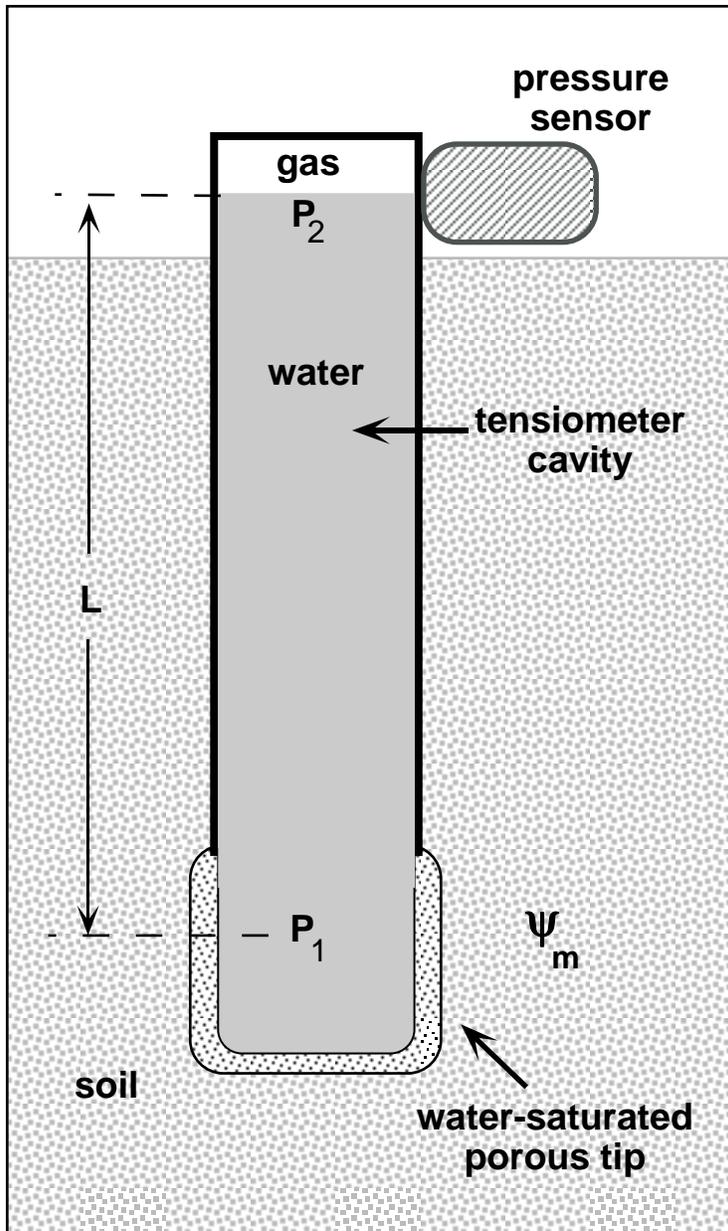
measurement with deeper installations because of the elevation-dependent hydrostatic pressure decrease. Such a conventional tensiometer used for depths greater than about 8 m with permit little to no useful measurements of matric potentials because the upper section of the column exists at low absolute pressure and rapidly becomes filled with water vapor. Approaches used to circumvent this problem eliminate use of the water-filled column and rely instead on either burying pressure transducers at or near the depth of the tensiometer tip or use of an air-filled column. The latter option is not as suitable for monitoring transient flow conditions since the air-filled cavity imparts low gauge sensitivity, hence a low response time.

Temperature variations in the field have long been known to make interpretation of tensiometer readings difficult. The phenomenon is complex and often sensitive to instrument design since thermal effects on volume changes of tensiometer components and fluids can be substantial. This can be especially problematic when instrument sensitivity is high and the overall tensiometer-soil conductance is low. Keeping all instrument components below the soil surface (where maximum temperature variations occur) can diminish temperature-induced changes in tensiometer readings. When tensiometers are used in field locations exposed to freezing temperatures, protection from damage by ice formation is necessary. This can be accomplished to an extent by adding methanol or antifreeze to the water in the tensiometer, or by burying the instrument below the depth of soil freezing.

### **Further Reading**

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### **Figure captions:**



**Figure 1.** Basic components of a tensiometer. When significant, the hydrostatic pressure difference acting over the vertical distance  $L$  between the measurement point and the tensiometer tip must be accounted for.

**Key words:**

Hydraulic potential  
 Hydrostatic equilibrium  
 Matric potential  
 Tensiometer  
 Unsaturated flow

**Suggestions for cross-referencing:**

Flow equations

Hydrodynamics

Hydrostatics

Thermodynamics of soil water

Vadose zone

**Terms and units**

|                         |   |          |
|-------------------------|---|----------|
| Density of water        | [kg m <sup>-3</sup> ]                   | $\rho_w$ |
| Acceleration of gravity | [m s <sup>-2</sup> ]                    | g        |
| Conductance             | [m <sup>2</sup> s <sup>-1</sup> ]       | K        |
| Head                    | [m]                                     | h        |
| Length (vertical)       | [m]                                     | L        |
| Matric potential        | [Pa]                                    | $\Psi_m$ |
| Pressure                | [Pa] or [kPa]                           | P        |
| Reading (tensiometer)   | [kPa]                                   | R        |
| Response time           | [s]                                     | $\tau$   |
| Sensitivity (gauge)     | [m <sup>-2</sup> ]                      | S        |
| Time                    | [s]                                     | t        |
| Volume                  | [cm <sup>3</sup> ] or [m <sup>3</sup> ] | V        |