An Alternative Tensiometer Design for Deep Vadose Zone Monitoring

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The conventional tensiometer is among the most accurate devices for soil water matric potential measurements, as well as for estimations of soil water flux from soil water potential gradients. Uncertainties associated with conventional tensiometers such as caused by ambient temperature effects and the draining of the tensiometer tube, as well as their limitation for deep soil monitoring, has prevented their widespread use for vadose zone monitoring, despite their superior accuracy in general. We introduce an alternative tensiometer design that offers the accuracy of the conventional tensiometer, while minimizing the aforementioned uncertainties and limitations. The proposed alternative tensiometer largely eliminates temperature-induced diurnal fluctuations and uncertainties associated with draining of the tensiometer tube and removes the limitation in installation depth. In addition, the manufacturing costs of this alternative tensiometer design are close to those of the conventional tensiometer, while it is especially suited for monitoring of soil water potential gradients as required for soil water flux measurements.

Abbreviations: AT, alternative tensiometer; CT, conventional tensiometer; PVC, polyvinyl chloride.

Soil water matric potential is critical for irrigation water management and scheduling, investigations of plant root water uptake, and general measurement of vadose zone processes such as estimation of water and solute leaching. The water-filled tensiometer is among the most accurate devices used for both laboratory experiments and in situ monitoring of soil water potential. The first design of a tensiometer was introduced by Livingston (1908) in a planted pot (Or, 2001).

A conventional tensiometer (CT) includes a water-filled tube, allowing measurement of the soil water matric pressure head, h_m, at the depth of the ceramic cup by a measurement device at or near the soil surface by way of a static column of water. Figure 1A shows a CT consisting of a ceramic cup, polyvinyl chloride (PVC) tube, transparent acrylic sighting tube, septum stopper, and pressure transducer. In this design, a ceramic cup is glued to the bottom of a 1.27-cm (½-inch) diameter water-filled PVC tube with the sighting tube at the top allowing water level monitoring. A pressure transducer is connected to the acrylic tube for continuous pressure monitoring inside the air-filled head space, which is assumed to be in equilibrium with the water pressure. The transparent sighting tube remains above the ground surface, allowing the user to observe the water level inside the tube. For this CT design, the tensiometer tube is maintained air-tight using a septum stopper, allowing manual pressure readings as well as refilling of the tensiometer with water, if so required.

We note that knowledge of the length of the static water column in the tensiometer tube is essential to accurately determine h_m at the depth of the ceramic

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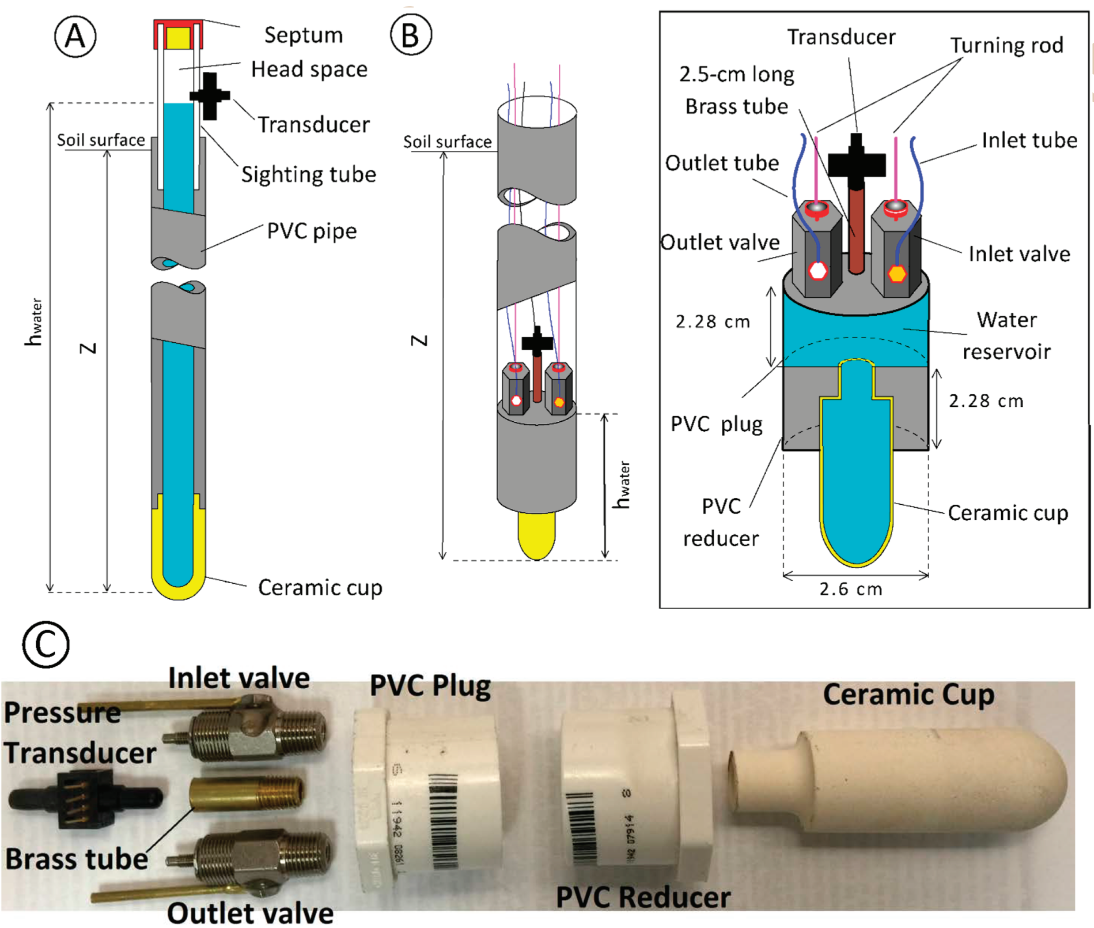

Fig. 1. (A) Schematic of conventional tensiometer design (CT) with septum stopper at the top; (B) schematic of the alternative tensiometer (AT); and (C) components of the alternative tensiometer design (AT).

cup (z) from pressure measurements near the soil surface (Fig. 1A). Specifically, the measurement range of h_m at depth z of the tensiometer cup is limited to ($-800 + h_{water}$) cm H_2O, with h_{water} denoting the height of the water column above the ceramic cup in the tensiometer tube. Unless the tensiometer tube is completely filled and the water level can be observed through a sighting tube near the pressure measurement device, the length of the static water column is unknown, leading to high uncertainty of the tensiometer readings. Specifically, Fig. 2A compares measurements of h_m from a pair of CTs at soil depths z of 220 and 250 cm in a field setting, showing that the uncertainty in h_m can be as large as the length of the tensiometer tube, as indicated by the differences between the assumed (vertical axis) and true (horizontal axis) h_m values. The correction to determine the true pressure of the partly drained tensiometer tube was determined from measurements of the volume of water at refilling of the tensiometer tube immediately after a manual transducer reading. In case of drainage of the tensiometer tube, the height of the water column in the tensiometer tube is unknown, and consequently, inferred h_m values may be severely overestimated (less negative). This uncertainty becomes even more important if we compare total head gradients using the measurements of this same pair of tensiometers, as presented in Fig. 2B. Specifically, the data show that gradient errors can be as large as fivefold and may lead to errors in the estimation of the flow direction, as inferred from the sign of the head gradient.

To eliminate errors associated with the unknown water column height, tensiometers were developed with the pressure transducer placed near the ceramic cup, such as the advanced tensiometer (Hubbell and Sisson, 1998) and UMS designs of T4 and T8 (UMS, 2011). Whereas the transducer unit of the advanced tensiometer needs to be brought to the soil surface for refilling, the UMS designs use small-diameter tubing to manually refill the tensiometer cup from the soil surface using a syringe. However, matric potential readings with these tensiometer types are affected by soil surface temperature fluctuations (Warrick et al., 1998), and the tensiometer range is limited by the depth of installation. Moreover, this device is prone to air entrapment in the small-diameter tubing, further amplifying temperature effects. In their special design, UMS (2007) developed the so-called *smart tensiometer* (TS1), using a miniature peristaltic pump to automatically refill the tensiometer cup by extracting water from the surrounding soil. Although highly beneficial for specific research projects, the TS1 is probably too complex for routine field applications.

Although in concept water-filled tensiometers are very accurate, their field application typically introduces errors associated with changing soil surface ambient temperatures and the draining of the water-filled tensiometer tube. We introduce here an alternative tensiometer (AT) design that eliminates the uncertainties associated with the CT but remains easy to use and affordable, allowing estimation of deep vadose zone water fluxes. The AT is designed such that it can be installed at large depths below plant rooting zones while providing high certainty in its readings and increasing its operating range to a matric water pressure head near −1000 cm. Furthermore, because of the inclusion of the pressure transducer near the ceramic cup, temperature fluctuations are largely eliminated. We note that the general concept behind the AT design is similar to that of the advanced and smart tensiometers. However, the AT design is affordable, with manufacturing costs close to that of the CT, and relatively simple to construct, with all the components commercially available.

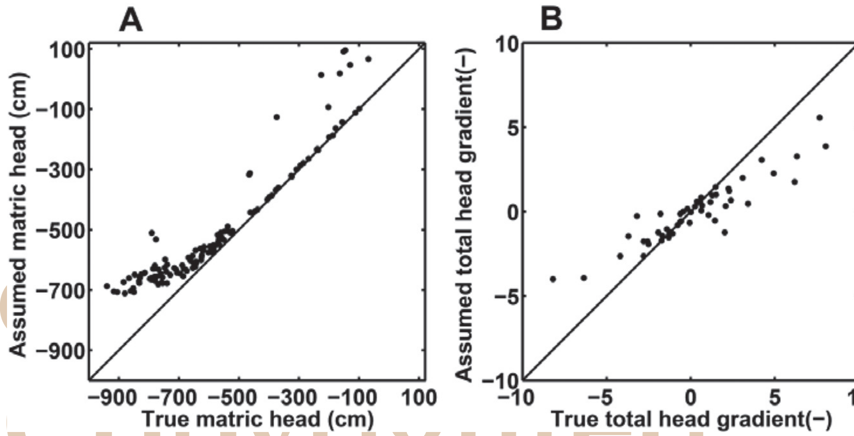

Fig. 2. A comparison of true (A) soil water matric head and (B) total head gradient with soil water matric head and total head gradients measured by a set of 240-cm and 270-cm-long conventional tensiometers. Values on the *y* axis assume that the tensiometer tube is full of water, whereas values along the *x* axis are those using the true water level in the tensiometer tube.

MATERIALS AND METHODS

The schematic and components of the AT design are shown in Fig. 1B and 1C. Components include a ceramic cup, small PVC water reservoir, two needle valves, two steel rods, two small-diameter lengths of Tygon tubing, a pressure transducer and 3.175-cm (1¼-inch) Schedule 40 PVC access pipe of length equal to the depth of the cup installation. The ceramic cup (Soilmoisture Equipment Corp., http://www.soilmoisture.com/, Part 0655X01-B01M1) was glued into the 1.27-cm (½-inch) opening of a 1-inch to ½-inch PVC reducer (Charlottepipe, http://www.charlottepipe.com/, reducer bushing, Part no. 2107). Two needle valves (Specialty Mfg. Co., http://www.specialtymfg.com/, Part no. MNV2SV-B, 1/8M, 1/16B) and a small $^{1}/_{16}$-inch-diameter and 1-inch-long brass tube (McMaster-Carr, Part no. 50785K258) were installed on top of the 1-inch PVC plug (Charlottepipe, plug, Part no. 2118). The pressure transducer (Honeywell, http://sensing.honeywell.com/, Part no. 26PCCFA6D) was connected to the brass tube. These two major components were glued together, thereby allowing for a sealed 12-mL water reservoir (height = 2.28 cm, diameter = 2.6 cm) in between. After testing for air-tightness, the completed assembly was connected to the bottom of a PVC access pipe, with the length equal to the installation depth. One needle valve is used to fill the tensiometer reservoir with water through the Tygon tubing, while the other needle valve allows simultaneous air release and excess water drainage. Two 2-mm-diameter steel rods allow opening and closing of the valves from the soil surface. The pressure transducer measures the air pressure in the small brass tube, assumed to be in equilibrium with the water of the tensiometer reservoir. Having both the transducer and water reservoir placed at the tensiometer cup depth minimizes the effect of soil surface ambient temperature fluctuations.

To evaluate the performance of the AT design, we conducted a sequence of controlled laboratory tests in a 30-cm-diameter flower pot. Both a prototype of the AT and a 25-cm-long CT were installed in the pot filled with a sandy loam soil, with tensiometer cups about 15 cm apart. The tensiometers were monitored for a 4-mo period, with six drying–wetting cycles. We also included two refilling events for the purpose of evaluating the tensiometers' performance after refilling of the tensiometer reservoir under both dry and wet soil conditions.

After completion of the laboratory tests, the AT was installed 30 cm away from a CT at a 200-cm soil depth below the drip line in an almond [*Prunus dulcis* (Mill.) D.A. Webb] orchard. Soil moisture conditions were such that h_m values were mostly outside the typical tensiometer range of −800 cm of water, thus requiring frequent refilling events.

RESULTS AND DISCUSSION

Figure 3 compares measurements of h_m with both the CT and the AT for six drying–wetting cycles of the laboratory test,

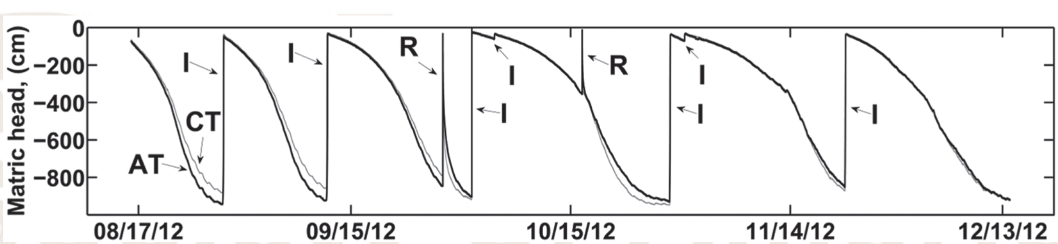

Fig. 3. A comparison between conventional (CT, thin gray lines) and the alternative tensiometer (AT, thick black lines), during six drying–wetting cycles (laboratory experiment). Irrigation and refilling events are marked as I and R, respectively.

showing similar responses by both tensiometers, as controlled by root water uptake, irrigation (I), and refilling of the tensiometer cups (R). Both tensiometer types closely agreed and showed no significant differences between h_m measurements. To evaluate the tensiometer response to the refilling events, both tensiometer types were opened for refilling with deionized water at h_m values near −350 and −800 cm of water. After closing the water reservoirs, both tensiometers needed a few hours to return to their prior h_m values when the soil was at or near −350 cm around 15 Oct. 2012; however, both tensiometers needed a few days to equilibrate for the dry soil conditions around 1 Nov. 2012. The much longer equilibration time was expected because of the decreasing soil hydraulic conductivity around the ceramic cup, as discussed by Durner and Or (2006).

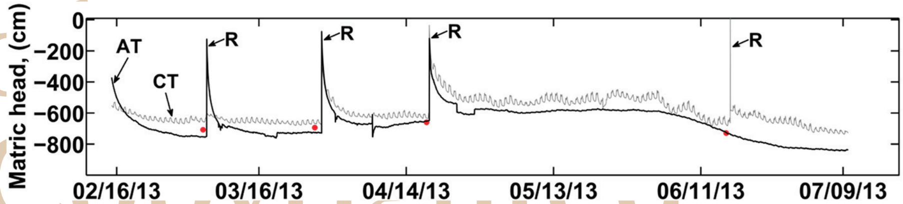

Fig. 4. A comparison between conventional (CT, thin gray lines) and alternative tensiometers (AT, thick black lines) for field experiments, representing measurements of soil water matric pressure head h_m at the 200-cm soil depth. Refilling events are marked as R. The last refilling event was done for the CT only, using a vacuum pump, to return the tensiometer pressure to its value before refilling. Red circles represent measurements of h_m at the 200-cm soil depth where the CT reading was corrected for the measured height of the water column before refilling events.

The comparison of the AT with the CT for the drip-irrigated almond orchard is presented in Fig. 4, where tensiometers readings represent h_m values at the 200-cm soil depth below the drip line. To correct the CT readings, we followed the standard practice and assumed that the height of the water column inside the tensiometer was equal to the tensiometer tube length. The field comparison clearly demonstrates the advantage of using the AT type, as diurnal fluctuations caused by temperature changes at the soil surface have almost completely disappeared, whereas fluctuations of the CT data are about 50 cm. Although both AT and CT show the same temporal dynamics of h_m, the operating range for the AT was extended to below −800 cm and is greater (more negative) than for the CT. In part, the differences in magnitude between the AT and CT tensiometer readings were probably caused by partial draining of the CT, causing both wetting of the soil around the ceramic cup as well as misinterpretation of the true soil water potential because of the unknown water column height. The red circles in Fig. 4 present the true soil water potential measured by the CT at refilling events, after the actual water column height was measured.

CONCLUSIONS

An AT was developed that includes all benefits of past tensiometer designs, eliminating their associated limitations and uncertainties while remaining easy to use and affordable. Uncertainties associated with the exact water column height were eliminated in the proposed AT by installing the pressure transducer near the ceramic cup. This design allows manual refilling of the tensiometer cup, while at the same time eliminating limitations of installation depth and fluctuations caused by changing air temperatures. These advantages may not seem as relevant for shallow tensiometer installations but are crucial for accurate measurements of soil water potential gradients across tensiometer pairs for deep vadose zone monitoring.

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