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Is the Tension Beneath a Tension Infiltrometer What We Think It Is?

C. Walker, H. S. Lin,* and D. D. Fritton

ABSTRACT

The tension infiltrometer has become a standard tool for measuring near-saturated soil hydraulic properties. The objective of this study was to examine the dynamics of the supply tension at the interface between the tension infiltrometer and the measured soil using a pressure transducer under different soil conditions and to raise some cautions needed for proper use of this standard device. Infiltration experiments were conducted on a tension table, a large sand column, and in two field soils of contrasting textures and structures to test the performance of the standard two-piece infiltrometer. Results showed that during high flow rates (>200 cm^3 min^{-1}) the tension at the infiltrometer–soil interface started to deviate by as much as 15 mm from the desired tension. However, during field experiments the high flow rates were not experienced, and thus no deviation was observed between the preset desired tension and the actual measured tension at the infiltrometer–soil interface. To alleviate the problem of tension deviation under high flow, the water supply tubing and fitting diameters of the standard infiltrometer were successfully increased to yield a higher flow rate (≈300–400 cm^3 min^{-1}) without elevated tensions.

Tension infiltrometers are widely used for determining soil hydraulic parameters such as saturated and unsaturated hydraulic conductivity, sorptivity, and macropore flow contribution (Angulo-Jaramillo et al., 2000; Ankeny et al., 1991; Casanova et al., 2000; Evett et al., 1999; Lin et al., 1997; Perroux and White, 1988; Watson and Luxmoore, 1986; White et al., 1992). The nondestructive nature of this instrument also allows for temporal investigations of soil hydraulic conductivity (Lin et al., 1998). The ease of use and relatively short operating times have provided the flexibility of making a large number of measurements to determine the spatial variability of hydraulic properties in different landscape settings and soil types (Lin et al., 1998; Watson and Luxmoore, 1986). The widespread use of the tension infiltrometer has facilitated field measurements of in situ soil hydraulic properties, inspired continued instrument improvements (Ankeny et al., 1988; Casey and Derby, 2002; Wang et al., 1998), and stimulated new analytical procedures for determining hydraulic properties from infiltrometer measurements (Ankeny et al., 1991; Logsdon and Jaynes, 1993; Reynolds and Elrick, 1991; Smettem and Clothier, 1989).

Wooding's solution for steady-state, three-dimensional flow into the soil from a circular source is the basis for unsaturated hydraulic conductivity calculations from infiltrometer measurements (Wooding, 1968). From this equation, many techniques have been developed to obtain various hydraulic parameters from steady-state tension infiltrometer measurements (Angulo-Jaramillo et al., 2000). A common solution to the Wooding's equation involves the use of simultaneous equations through a pair of supply tensions (Ankeny et al., 1991; Reynolds and Elrick, 1991) or disc sizes (Smettem and Clothier, 1989; Wang et al., 1998). All calculations of hydraulic properties from tension infiltrometer data rely on the assumption that the supply tension at the infiltrometer disc–soil interface is constant and is not dependant on soil conditions.

This study investigates the assumption of constant supply tension at the interface between infiltrometer disc and the contacted soil of the standard two-piece tension infiltrometer. We also investigated the upper flow limit of the two-piece tension infiltrometer and potential modifications designed to increase the flow of water without increasing the tension in the disc.

MATERIALS AND METHODS

The tension infiltrometer used in this study was a two-piece unit (Fig. 1), which was designed according to the specifications described by Perroux and White (1988) and is consistent with commercially available models. However, to improve flow-monitoring accuracy, the unit was adapted to accommodate multiple reservoir sizes. The reservoir base, constructed from 51-mm-diameter PVC pipe, was attached to a flexible coupling (American Valve, Greensboro, NC) to allow for a quick change between different sizes of reservoirs. The reservoirs were equipped with an Omega PX26-005 DV differential pressure transducer (Omega Engineering, Stanford, CT) to monitor water height change in the reservoir. The inner diameter of the air entry tube in the bubbling tower was 3.2 mm. The tubing and fittings that linked the bubbling tower to the reservoir also had a 3.2-mm i.d. The 600-mm section of tubing and barbed fittings used to connect the reservoir to the infiltration disc had inner diameters of 12.7 and 8.7 mm, respectively. The infiltration disc had an effective diameter of 232 mm.

To monitor the tension between the infiltrometer disc and the contacted soil surface, we attached an Omega PX26-001 DV pressure transducer to the disc, using a 100-mm section of plastic tubing (3.2-mm i.d.) (Fig. 1). The tubing was used to prevent the transducer from getting wet while the disc was submerged to remove air bubbles. The transducer was installed 30 mm from the center of the disc. With this setup, it was possible to monitor the actual tension applied to the soil surface using a datalogger and a laptop and to make real-time adjustments to the tension setting so the desired tension could be achieved. This study used a Campbell CR-10 datalogger (Campbell Scientific, Logan, UT) to monitor the water tension transducer as well as the water height transducer attached to the water reservoir.

We calibrated the water tension transducer by placing it on a pre-saturated tension table equipped with grade 470 filter paper (S & S Filter Paper, Schleicher & Schuell, Keene, NH). To ensure zero tension in the disc, the infiltrometer's water supply valve was opened before calibration started. However, during calibration the valve remained closed. The tension

Dep. of Crop and Soil Sciences, 116 ASI Building, The Pennsylvania State Univ., University Park, PA 16802. Received 14 Jan. 2005. *Corresponding author (henrylin@psu.edu).

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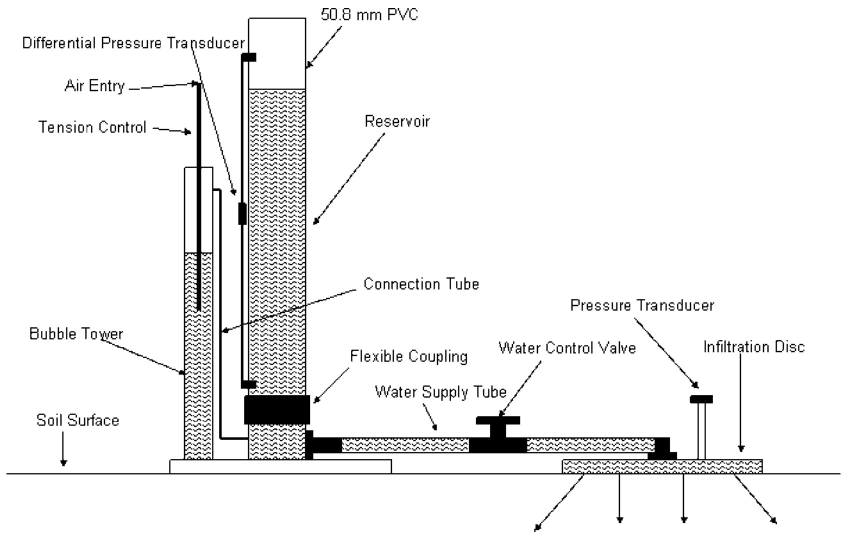

Fig. 1. Schematic a two-piece tension infiltrometer. The two-piece tension infiltrometer includes an additional pressure transducer on the infiltration disc. The flexible coupling allows for quick changes between different reservoir diameters, providing for more accurate water height measurements for different flow rates.

settings on the infiltrometer were calibrated by using a U-tube manometer and then were verified with the pressure transducer. The slope and intercept from the calibration linear regression equation was programmed into the datalogger to provide a real-time tension monitoring capability.

Laboratory experiments were performed both on the tension table and on a large sand column. The tension table was chosen to provide a method of controlling the flow rate, whereas the large sand column provided a natural but controlled high-flow setting. Laboratory setup for the infiltrometer mimicked a field situation. The tension infiltrometer was placed at an even elevation with the tension table and was set to the desired tension. The infiltrometer was turned on and the tension table was adjusted to simulate different flow rates. We were able to increase and decrease the flow rates for the experiment by varying the height of the tension table. The tension setting on the tension infiltrometer was kept constant while the height of the tension table was varied. Tension measurements from the pressure transducer were recorded every 2 s with the datalogger. Each tension was measured for at least 5 min after steady state had been achieved. The sand column experiments were performed on a drained cylinder of medium sand (cylinder 550 mm in diameter by 700 mm in height). Measurements were performed on the sand column at 120, 60, 30, 20, 10, and 0 mm tensions sequentially (with 10 min for 120-mm tension, 5 min for 60 to 20 mm, and 3 min for 10 and 0 mm), following the procedures similar to that of Lin et al. (1997). The sand column had a laboratory-measured saturated hydraulic conductivity of 2.0 cm min^{-1}.

To verify the constant tension assumption, we conducted field measurements on two different soil types. These measurements were performed using three identical tension infiltrometers as replicates. Each infiltrometer was equipped with two pressure transducers, one to measure water height change in the reservoir (flow) and the other to measure the actual tension in the disc. Site preparation followed that of Lin et al. (1997), and included trimming vegetation, installing a retention ring, placing a layer of cheesecloth on the soil surface, and making the area even with thin layer of very fine sand. The water reservoir was placed next to the infiltration area and was even with the tension disc. The infiltration measurements were conducted at the same sequence of supply tensions as the sand column experiments, but the time period for each supply tension was longer (with 30 min for 120- and 60-mm tensions, 20 min for 30- and 20-mm tensions, and 15 min for 10- and 0-mm tensions). The pressure transducer in the infiltration disc was used solely to record the actual tension in the disc during the infiltration, not to make real time adjustments.

The field studies were conducted on two soils of contrasting textures and structures. The Hagerstown series (Typic Hapludalf) in a cropland is a limestone-derived residual soil that is very deep and well drained, with a moderate permeability. The surface texture of the soil is silt loam, and the surface structure is fine subangular blocky to granular. The Morrison series (Ultic Hapludalf) in a forest is a noncalcareous sandstone-derived residual soil that is very deep and well drained, with moderate to moderately rapid permeability. The surface texture is loamy sand with a granular to single grain structure. The laboratory-measured saturated hydraulic conductivity values of both soils were <0.1 cm min^{-1}.

To increase the maximum flow rate of the two-piece tension infiltrometer, this study evaluated modifications to the water supply tube. The internal diameter of the tube connecting the water reservoir to the tension plate was increased from 12.7 to 15.9 mm, and the internal diameters of the barbed fittings were also enlarged from 8.7 to 13.2 mm. The water supply valve was replaced with a 15.9-mm PVC plumbing valve attached directly to the reservoir. By retrofitting the infiltrometer with the larger fittings and tubing, we increased the smallest orifice diameter from 8.7 to 13.2 mm.

To mathematically solve for head loss through the water supply orifices in the tension infiltrometer, both the orifice equation and the Darcy–Weisbach equation were used. The different components were considered to be in series with each other, and plotted as total head loss. The orifice equation is described as (Jarrett, 2000):

$$q = ca\sqrt{2gh} \quad [1]$$

where q is flow (m^3 s^{-1}), c is the orifice coefficient (0.6, based on the shape of the orifice), a is the area of the orifice (m^2) (barbed tube fittings), g is gravity (m s^{-2}), and h is the pressure difference (m). The Darcy–Weisbach equation is described as (Viessman and Hammer, 1998):

$$\Delta t = \lambda(L/d_n)(v^2/2g) \quad [2]$$

where Δt is the change in tension (m), λ is the friction factor (64/Reynolds number), L is length of pipe (m), d_n is diameter (m), v is velocity (m s^{-1}), and g is gravity (m s^{-2}). It was determined that the flow through this instrument was laminar flow (Reynolds number < 2000), so the equations are valid.

RESULTS AND DISCUSSION

Figure 2 shows the response of the infiltrometer's infiltration disc when subjected to different flow rates on the tension table. As the flow rate increased beyond approximately 200 cm^3 min^{-1}, the disc's tension started to increase by as much as 15 mm over the desired tensions. This elevated tension occurred even though the tension-setting tube was not changed during the experiment. These results suggest that, depending on the soil type being measured and its permeability, the two-piece tension infiltrometer has the possibility of voiding one of the primary assumptions of the instrument, that is, maintaining a constant supply tension. The increase in tension at the disc was positively related to the flow rate for all of the supply tensions tested (Fig. 2). However, the standard deviation of the tension was roughly inversely related to the increase in the flow rate. This increase in the standard deviation of the measured tension at low flows visually corresponded to the air bubbling through the air entry tube. The 200 cm^3 min^{-1} threshold was chosen because the tension had a noticeable increase shortly after reaching this value.

The elevated tension with respect to flow rate was also detected in the sand column experiments. Figure 3 depicts the measured tension in the tension disc during the sand column experiments. When the instrument was set to a tension of 120 mm, the measured and the desired tensions were similar. However, when the instrument was set to lower tensions of 60, 30, 20, 10, and 0 mm, the calibrated and the measured tensions started to deviate from each other more and more (Fig. 3). Even though the instrument was set to 0-mm tension, the actual tension was recorded to be approximately 30 mm (Fig. 3). The flow rates for the 120-mm tension were below the threshold rate of approximately 200 cm^3 min^{-1}, whereas the flow rates for the lower tensions were between 400 and 750 cm^3 min^{-1}.

Field experiments were conducted to determine if there was any tension deviation from the calibrated value. Figures 4 and 5 show the results obtained from the Hagerstown silt loam and Morrison loamy sand, respectively. Overall, the tensions measured with the pressure transducer match up within a 10-mm range of the calibrated tension throughout all the tensions tested (120–0 mm range). The small deviation (<10 mm) from the calibrated tensions may be attributed to a combination of several factors, including small difference in height between the base of the infiltrometer reservoir and the tension disc, air bubbling, and temperature fluctuation during the field measurements. We noticed that the tension disc has a slight tendency to sink after the measured soil has been moistened, which contributed to the difference between the actual and calibrated tensions. The flow rates calculated for each infiltrometer were all below the 200 cm^3 min^{-1} threshold value. These

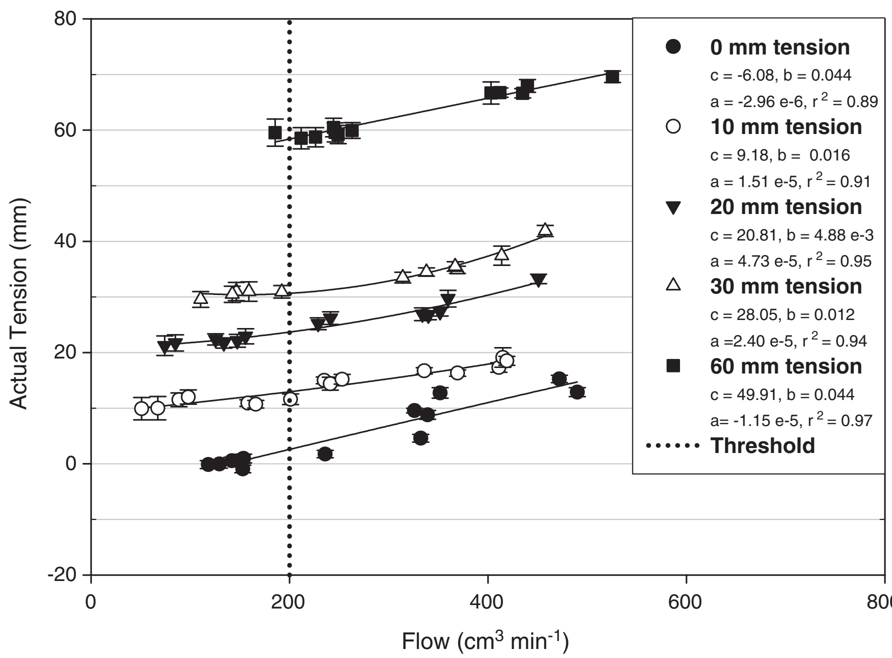

Fig. 2. Measured tension at the infiltration disc versus flow rate for the tension infiltrometer on a tension table using the standard water supply tube and fittings (12.7 and 8.7 mm, respectively). The tension control was set to the desired tension of either 0, 10, 20, 30 or 60 mm and remained so while the flow rates were varied. The starting point for each curve was the lowest constant flow rate measured. The flow rate was then increased by elevating the tension on the tension table. The error bars represent the standard deviation of the measured tension during each steady-state measurement. The coefficients of the quadratic equation, which was fitted to the points of each desired tension, are shown in the legend of the graph [$(a)x^2 + (b)x + (c)$]. The dotted vertical line (threshold) represents the approximate flow rate in which the tension starts to increase considerably.

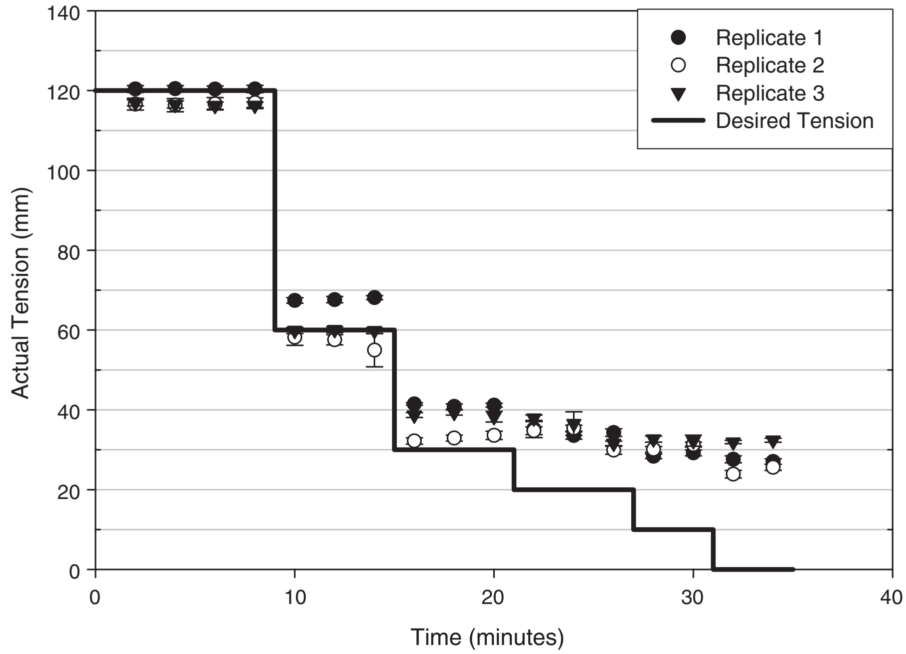

Fig. 3. Replicate measurements of tension in the infiltration disc while on a sand column for six desired tensions, 120, 60, 30, 20, 10, and 0 mm, respectively. Each point on the graph represents 2-min tension averages with the standard deviation shown by error bars. The solid line represents the desired tension setting of the infiltrometer.

results indicate that the present design for the infiltrometer works well in these two natural conditions. Nevertheless, caution should be taken when conducting measurements in areas of faster flow, such as golf greens, recently tilled soils, or other highly permeable soils, because there may be restrictions on flow caused by inadequate tubing sizes leading to tension deviations as those shown in Fig. 3.

From observations made during the tension table and the sand column experiments, the volume of water flowing from the infiltrometer reservoir to the disc appeared to have a direct influence on the measured tension in the tension disc. It was hypothesized that the barbed tube fitting connecting the piece of 12.7-mm tubing from the reservoirs to the valve may be limiting the water flow to the tension disc. To substantiate this

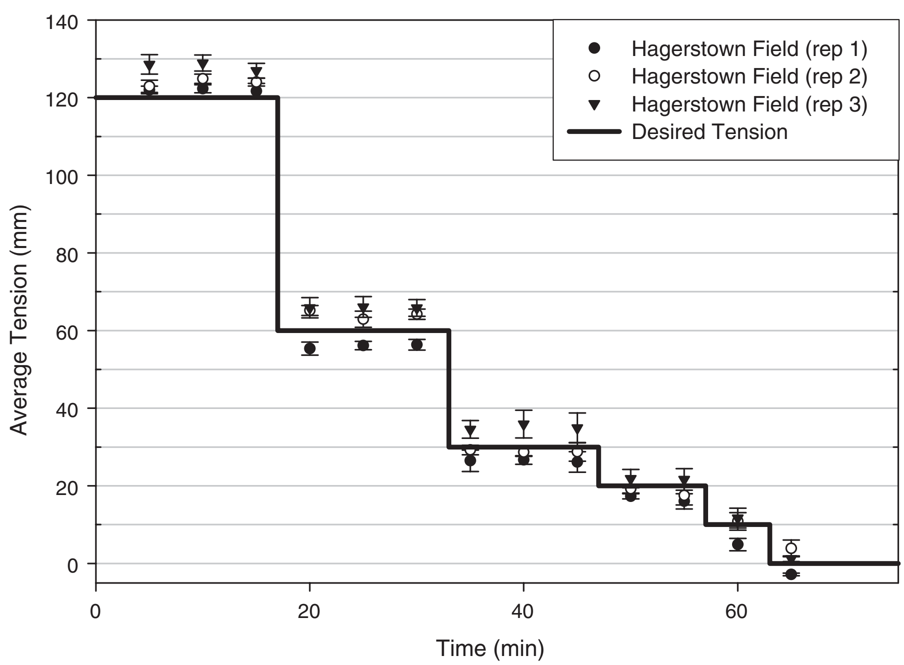

Fig. 4. Replicate measurements of tension in the infiltration disc placed on the Hagerstown silt loam soil for six desired tensions, 120, 60, 30, 20, 10, and 0 mm, respectively. Each point on the graph represents 5-min tension averages with the standard deviation shown by error bars. The solid line represents the desired tension setting of the infiltrometer.

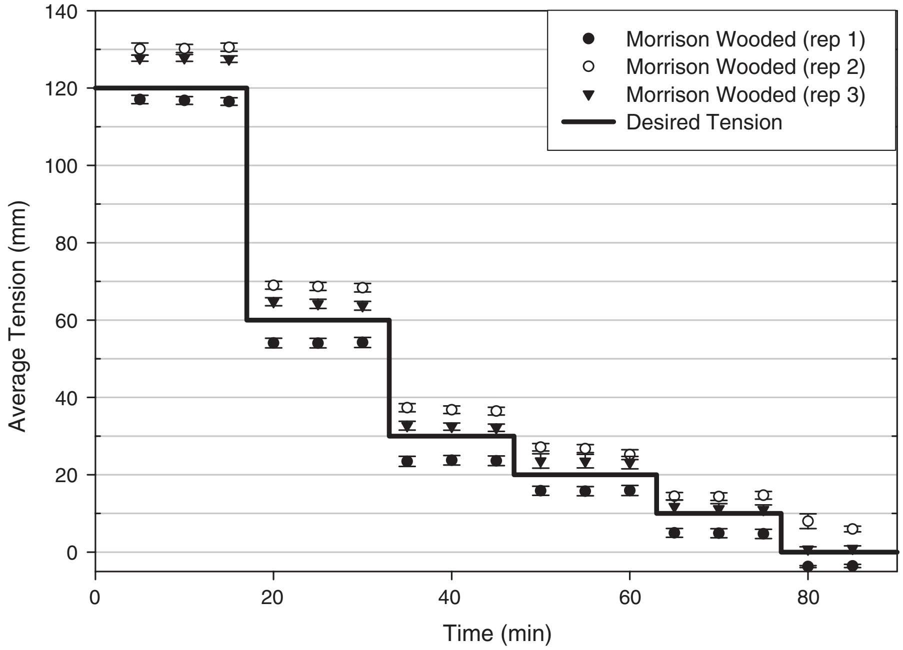

Fig. 5. Replicate measurements of tension in the infiltration disc placed on the Morrison sandy loam soil for six desired tensions, 120, 60, 30, 20, 10, and 0 mm, respectively. Each point on the graph represents 5-min tension averages with the standard deviation shown by error bars. The solid line represents the desired tension setting of the infiltrometer.

idea, both the orifice equation (Eq. [1]) and the Darcy–Weisbach equation (Eq. [2]) were used to calculate the increase in tension through the pipe network due to friction. These calculations were performed for a range of flow rates and the results are depicted in Fig. 6. The increase in tension shown from the calculations is similar to the laboratory results reported previously.

To determine if the water supply tube was the problem, the tubing, barbed fittings, and the water supply valve were all replaced with larger ones. The results obtained using the increased diameters of the tubing, barbed fittings, and valves indicated that the tension remained steady beyond the flow rate of approximately 200 cm^3 min^{-1}, but started to rise (drift away from calibrated tension) after >300 to 400 cm^3 min^{-1} flow rate (Fig. 7). This suggests that the water supply tube and fittings may be the cause of the rising tension under high flow rates in the standard two-piece infiltrometer. There did not appear to be any adverse effects from increasing the tubing diameter, except a slight increase

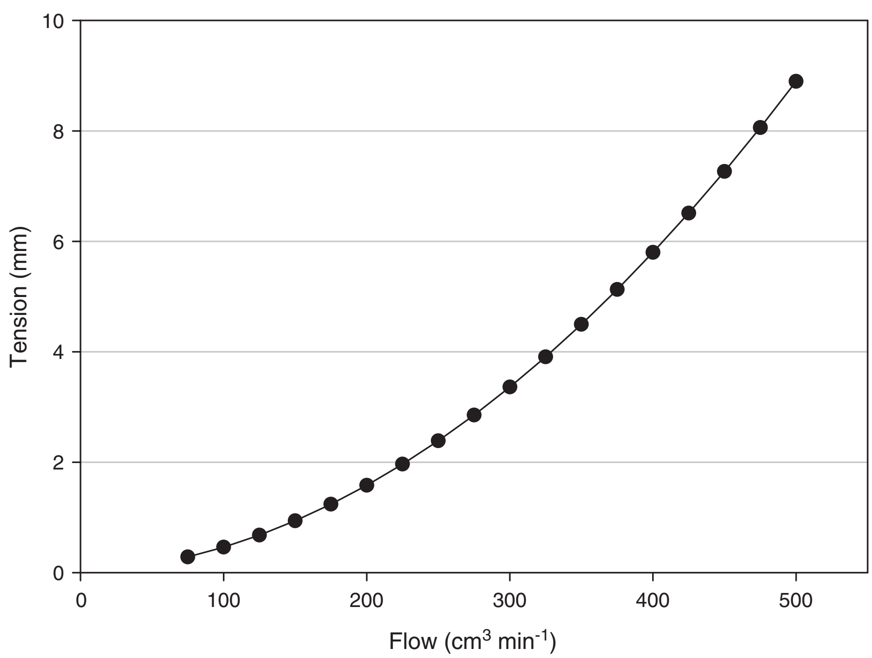

Fig. 6. Results from the tension calculations. The increase in tension, due to friction, was calculated using the orifice equation and the Darcy–Weisbach equation. The tension increase was calculated for flow rates from 75 to 500 cm^3 min^{-1}.

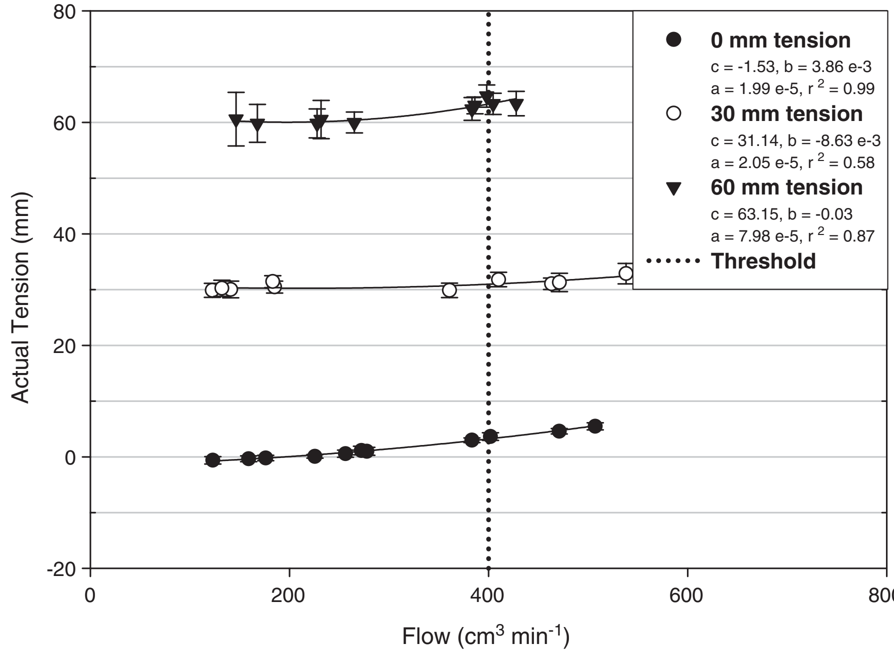

Fig. 7. Measured tension at the infiltration disc versus flow rate for the tension infiltrometer on a tension table using the larger water supply tube and fittings (15.9 and 13.2 mm, respectively). The tension control was set to the desired tension of either 0, 10, 20, 30, or 60 mm and remained so while the flow rates were varied. The starting point for each curve was the lowest constant flow rate measured and then the flow rate was increased by elevating the tension on the tension table. The error bars represent the standard deviation of the measured tension during each steady-state measurement. The coefficients of the quadratic equation, which was fitted to the points of each desired tension, are shown in the legend of the graph [$(a)x^2 + (b)x + (c)$]. The dotted vertical line (threshold) represents the approximate flow rate in which the tension starts to increase considerably.

in the standard deviation of the tension at the 60-mm supply tension as compared with the smaller tube.

CONCLUSIONS

This study suggests that in many field situations, the present standard design of the two-piece tension infiltrometer is fully capable of maintaining a constant tension at the infiltrometer–soil boundary, if used properly. However, in some circumstances, where flow rates are very high (e.g., in golf greens, cracked soils, and soils with a coarse sandy texture), caution should be taken to avoid the drift of supply tensions. This is important to the accurate use and interpretation of tension infiltrometer measurements since these devices are most frequently used for determining near-saturated hydraulic parameters in macroporous soils where flow rate could be high. Retrofitting the infiltrometer with larger tubing and fittings will help maintain a constant tension under conditions of high flow rates.

Proper infiltrometer setup is also important to accurate measurements. If the infiltrometer water reservoir is not level with the tension disc when using the two-piece unit, then there will be a discrepancy between the calibrated tension and the actual tension at the instrument–soil boundary. In such situations, it would be desirable to use a pressure transducer to monitor the actual tension on a real-time basis. The addition of a pressure transducer on the tension disc, as used in this study, allows for flexible tensions to be applied to the soil. This added pressure transducer is also helpful during measurement to detect any problems that may be occurring (such as leaks or air bubbles) and to make real-time adjustment.

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