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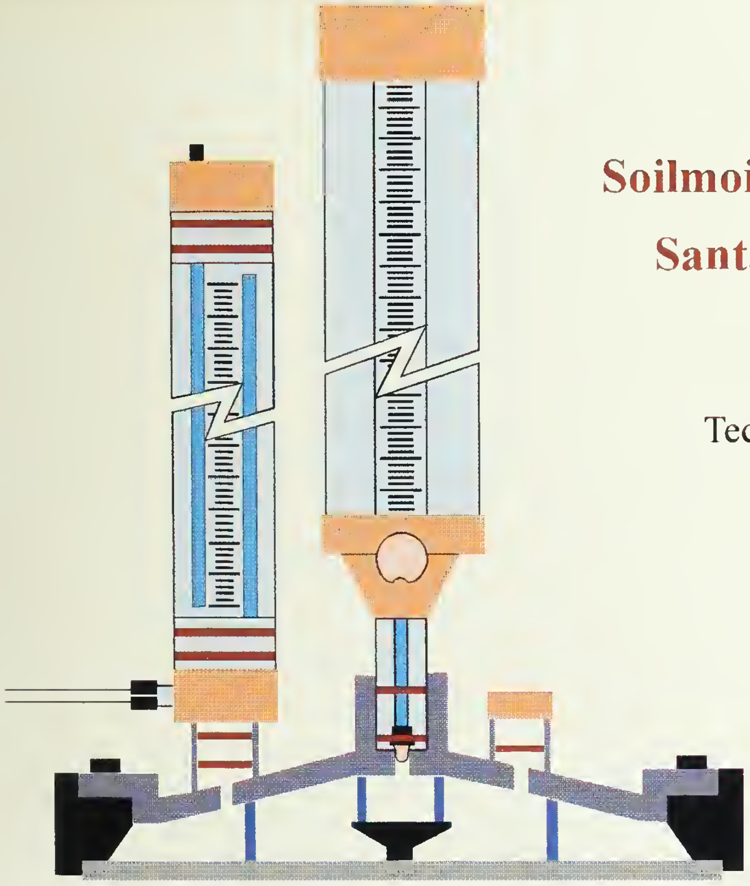
PERFORMANCE ASSESSMENT OF THE TENSION INFILTROMETER



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by

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Contents

Tables

Figures

1. Introduction

The tension infiltrometer (TI) is a field apparatus for in-situ determination of near-saturated hydraulic conductivity, K(h), where "near-saturated" refers to measurements made over the tension or negative pressure head (h) range, $0 \leq h \leq 20$ cm of water. The apparatus operates by measuring the infiltration rate (recharge) into the soil through a porous disk or membrane on which a constant water tension is applied by a "bubble tower" (Fig. 1). The K(h) values are obtained by measuring a sequence of infiltration rates corresponding to a sequence of tensions set on the bubble tower, and then applying theoretical relationships given in Reynolds (1993), Ankeny (1992), Elrick and Reynolds (1992) and White et al. (1992).

Tension infiltrometers have just recently moved from the realm of "research prototype" to "commercial product", and are currently marketed by A.L. Franklin Pty. Ltd., Sydney, Australia; Soil Measurement Systems, Tucson, Arizona; and Soilmoisture Equipment Corporation, Santa Barbara, California. The information available on performance attributes and maintenance is somewhat limited for all of these "commercial" TI's, but particularly so for the unit marketed by Soilmoisture Equipment Corp. Specifically, Soilmoisture provides no information on the hydraulic properties and maintenance of the porous disk, or on the calibration of the bubble tower. As detailed knowledge of these attributes is critical to the successful operation of tension infiltrometers, this performance assessment of the Soilmoisture TI was undertaken to establish the wettability, bubbling pressure and hydraulic conductivity of the porous disk (disk hydraulic properties), and the accuracy, linearity and resolution of the bubble tower (bubble tower calibration). Brief comments and recommendations are also given concerning maintenance of the porous disk, and operation of the TI in the field. A total of 10 Soilmoisture TI's were assessed. Note that the Soilmoisture TI is occasionally referred to as the "Guelph Tension Infiltrometer" (GTI) because it is designed as an attachment to their "Guelph Permeameter", which they have marketed for several years.

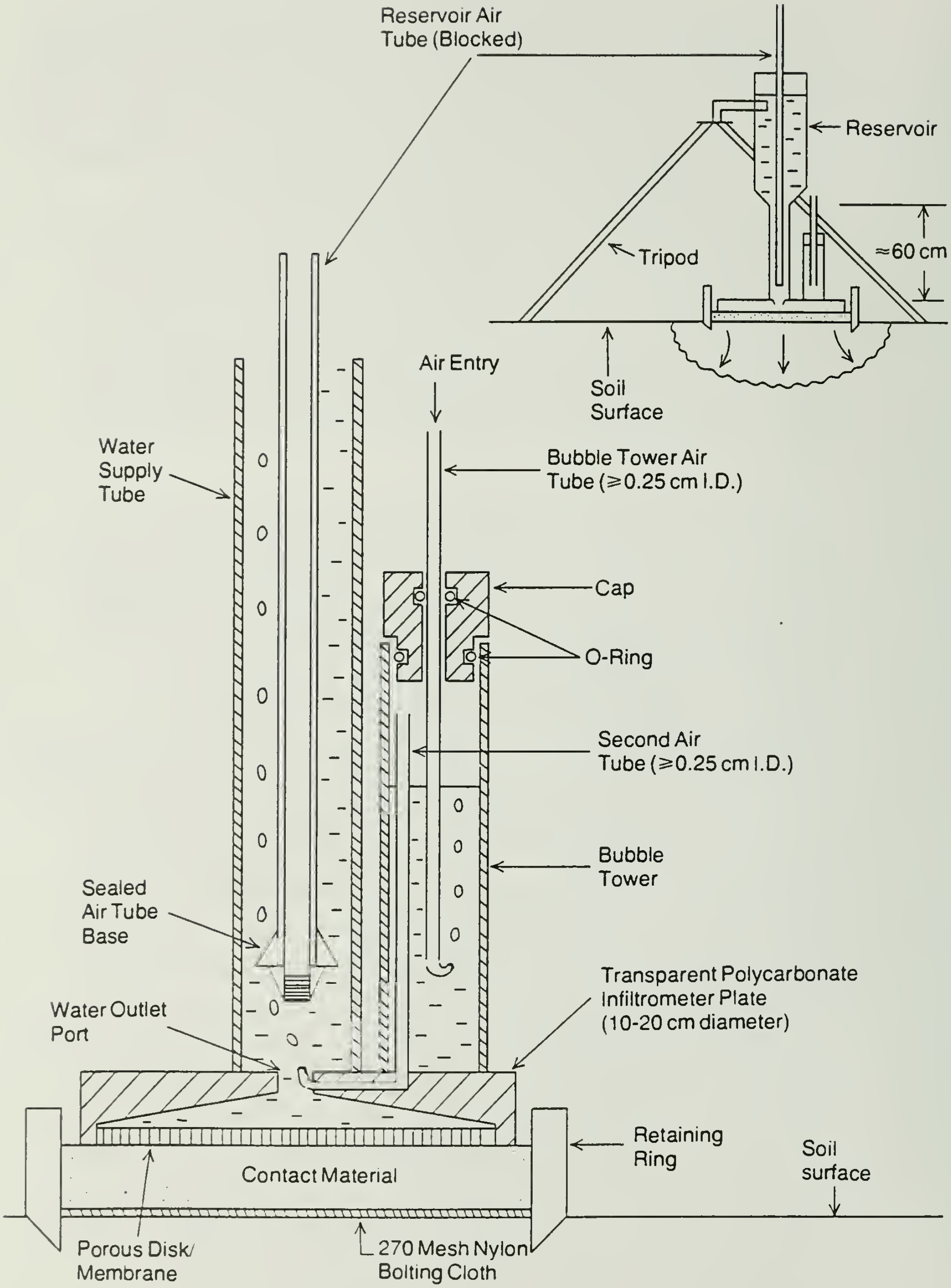

Figure 1. Schematic of a mariotte-based tension infiltrometer (after Reynolds, 1993).

2. Wettability and Bubbling Pressure of the Porous Disk

The porous disk or membrane in any TI (Fig. 1) must be hydrophillic (water wettable) and have a distinct bubbling pressure (air entry value) that is greater than the maximum tension to be applied by the bubble tower. The porous disks in the Soilmoisture TI's did not wet spontaneously when first placed in de-aired, temperature-equilibrated tap water, even when left standing in the water for several days. The disks did wet, however, when vacuum was applied. The bubbling pressure of the disks was found (using the procedures in Reynolds, 1993) to be approximately 30–35 cm of water, which exceeds (as is required) the maximum tension that can be applied by the bubble tower (approximately 25 cm of water).

It is desirable for the porous disks to wet spontaneously (i.e. without applying a vacuum) when placed in water, as this produces a greater degree of saturation of the disk and consequently a greater disk conductivity (discussed further in Section 3). The disks in the Soilmoisture TI's consist of porous polyethylene plastic that has been treated with a chemical surfactant to induce wettability (polyethylene is naturally hydrophobic, i.e. non-water wetting). We found that their wettability can be improved to the point of spontaneous wetting by submerging the disks in a surfactant solution (49% by vol. isopropyl alcohol, 49% by vol. distilled water, 2% by vol. Triton X 100 surfactant) for 24–36 hours.

3. Hydraulic Conductivity of the Porous Disk

The saturated hydraulic conductivity (Ksat) of the porous disk should be greater than the field-saturated and near-saturated hydraulic conductivity of the porous material being tested. Otherwise, the disk may restrict water infiltration, which may in turn result in underestimates of the conductivity of the porous material. The Ksat values of the Soilmoisture disks after initial saturation are given in Table 1. The mean Ksat of 1.30×10^{-3} ($\pm 0.248 \times 10^{-3}$) cm/s is about an order of magnitude lower than what one might consider as ideal, since the field-

Table 1. Saturated hydraulic conductivity (Ksat) of the Soilmoisture TI porous disks after initial saturation from an air-dry state.

TI Ident. No.	10^3 Ksat$^+$ (cm/s)
1	0.896
2	1.70
3	1.40
4	1.33
5	1.51
6	1.62
7	1.18
8	1.19
9	1.10
10	1.04
Arithmetic Mean	1.30
Standard Deviation	0.248

$^+$ measured using the falling head method

saturated hydraulic conductivity of most agricultural soils is $\leq 10^{-2}$ cm/s. When the disks were treated with the surfactant solution, the mean Ksat increased by about a factor of 2.6 to 3.32×10^{-3} ($\pm$ 0.292×10^{-3}) cm/s. This increase apparently reflects a greater degree of disk saturation resulting from the increased wettability. When some of the disks were re-wetted after about 3 months storage in an air-dry state, the mean Ksat had dropped to 1.65×10^{-3} ($\pm$ 0.169×10^{-3}) cm/s, which may suggest that the disks require periodic re-treatment with surfactant (say, every 2–4 months) in order to maintain maximum Ksat.

Although the Ksat of Soilmoisture's porous disk is lower than ideal, it should still be quite adequate for most agricultural soils, particularly for measuring the near-saturated conductivities which are often more than an order of magnitude less than the field-saturated value. As discussed above, K(h) results that are greater than or equal to the Ksat of the porous disk (i.e. greater than about 3×10^{-3} cm/s) should be treated with caution. The minimum hydraulic conductivity that can be measured conveniently by Soilmoisture's TI system appears to be about 10^{-6} cm/s, which gives the TI a K(h) range of about 3×10^{-3} cm/s to 1×10^{-6} cm/s. The minimum K(h) is determined primarily by the bubbling pressure of the porous disk/contact sand, and the minimum infiltration rate that can be measured accurately within a practical period of time.

4. Porous Disk Leakage Problems

The seal between the porous disk and the aluminum support ring (Fig. 2) must be air-tight to prevent air leaks when tension is applied to the disk. This seal, which is made with glue in the Soilmoisture design, failed in several of the units when measuring the Ksat of the porous disk. The problem appeared to be the inability of the glue to grip the anodized aluminum support ring. All alternative glues tried (including epoxies such as Conap) also failed to grip the aluminum adequately. This situation was resolved by machining a step into the porous disk and attaching an aluminum "retaining ring" (Fig. 3). A bead of silicone (G.E. silicone "gasket maker") was placed between the porous disk and support ring, and between the porous disk and retaining ring (Fig. 3). The silicone forms an air-tight seal, but still allows the disk to be easily removed if required. The retaining ring supplies the mechanical force required to hold the porous disk in place and to maintain the integrity of the seal. The porous disks were re-treated with wetting agent after the installation of the retaining rings in order to make the surfaces of the silicone seal water wettable.

5. Bubble Tower Calibration

The accuracy, linearity and resolution of the TI bubble tower for setting the tension on the porous disk was determined using a tension table-hanging water column arrangement, and procedures similar to those given in Reynolds (1993). In essence, the TI's were placed on the tension table, a range of tensions were set on the bubble towers, and the resulting steady state tensions on the porous disks were read via the hanging water column. The accuracy and linearity of the bubble towers were assessed by determining the least squares

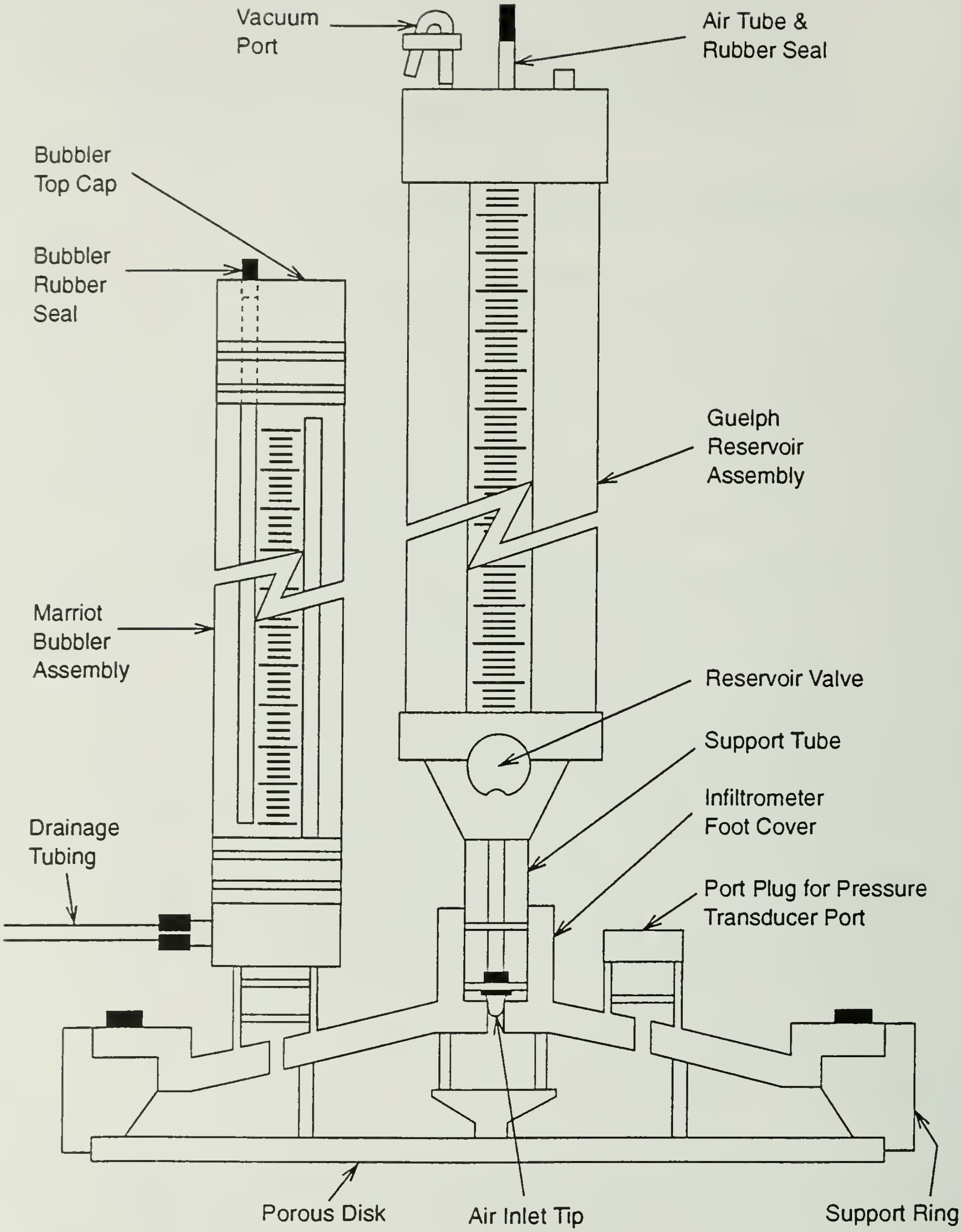

Figure 2. Schematic of the tension infiltrometer marketed by Soilmoisture Equipment Corp. (after Soilmoisture Equipment Corp., Santa Barbara, California).

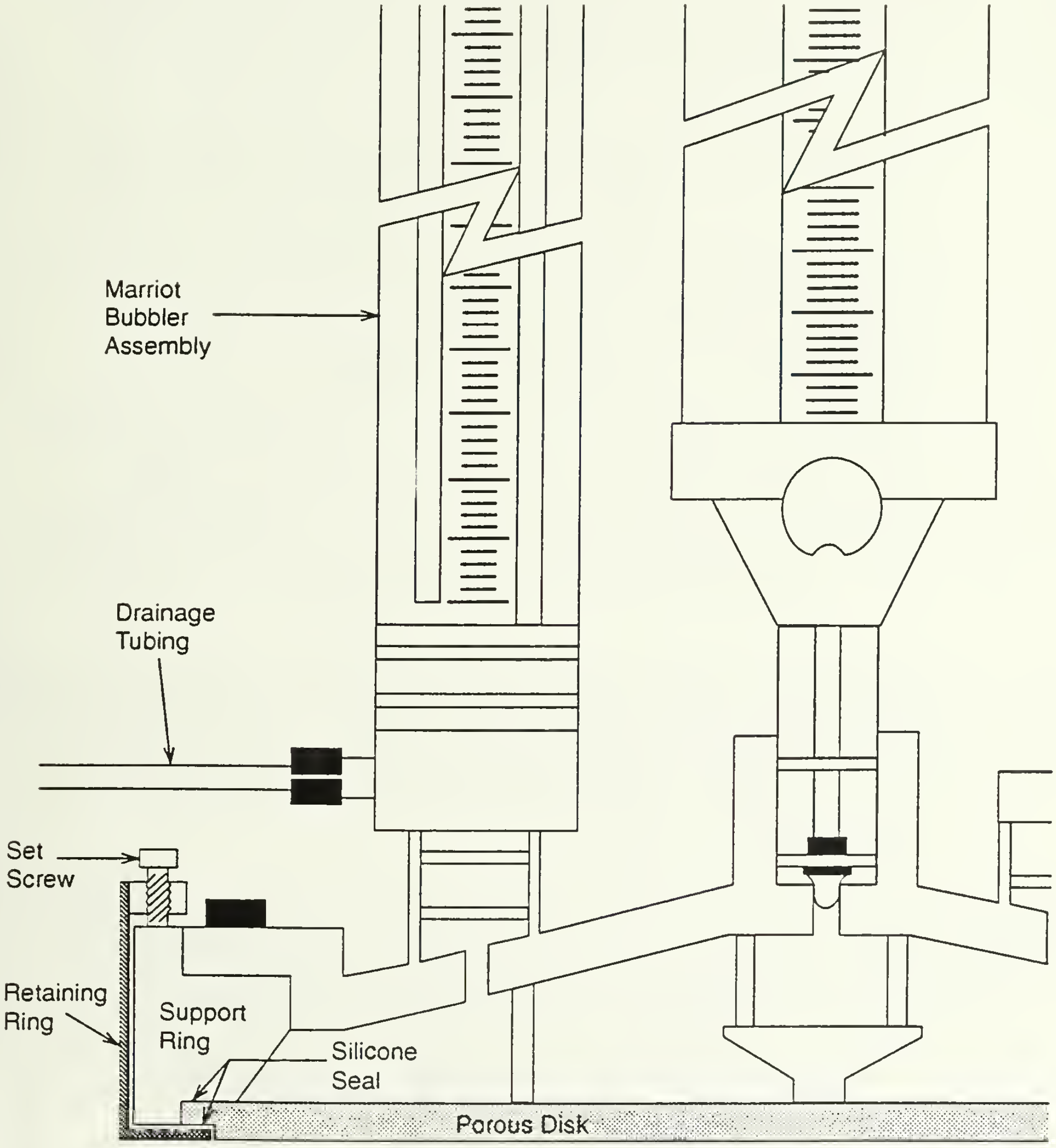

Figure 3. Schematic of the aluminum retaining ring attachment for the Soilmoisture Equipment tension infiltrometer.

regression relationship between the tension set on the bubble tower (Y-axis) and the tension measured by the hanging water column (X-axis). The tensions used were approximately, 24, 15, 7 and 1 cm of water, which effectively covers the full range of tensions available on the bubble tower. The resolution of the bubble towers was estimated by observing the oscillation in measured tension over time (as determined by hanging water column) for particular bubble tower tensions.

The least squares regression coefficients and R-squared values for each TI are given in Table 2. A summary plot of bubble tower tension vs. hanging water column tension for all 10 TI's is given in Fig. 4, along with the corresponding regression line and the 1:1 line. It is seen in Table 2 that the regression relationships are very similar and highly linear, with a mean slope of 1.0001 (± 0.0053), a mean intercept of –1.6548 (± 0.1818) cm, and a mean R-squared of 0.99997 (± 0.0000293). This is confirmed in Fig. 4, where the regression slope, intercept and R-squared values are 0.9998, –1.6514 and 0.9997, respectively. The bubble towers are consequently very similar

Table 2. Least squares regression relationships between set bubble tower tension (Y) and measured hanging water column tension (X), Y = aX + b, and the corresponding coefficients of determination, R-squared.

TI Ident. No.	a	b (cm)	R-Squared
1	1.0102	–1.8360	0.99997
2	1.0001	–1.5394	0.999898
3	0.9878	–1.2620	0.99996
4	1.0023	–1.4928	0.99998
5	0.9983	–1.5640	0.999997
6	0.9980	–1.7349	0.999998
7	1.0035	–1.7846	0.99997
8	1.0000	–1.6500	1.0000
9	0.9989	–1.8107	0.99998
10	1.0017	–1.8735	0.99995
Arithmetic Mean	1.0001	–1.6548	0.99997
Standard Deviation	0.0053	0.1818	0.0000293

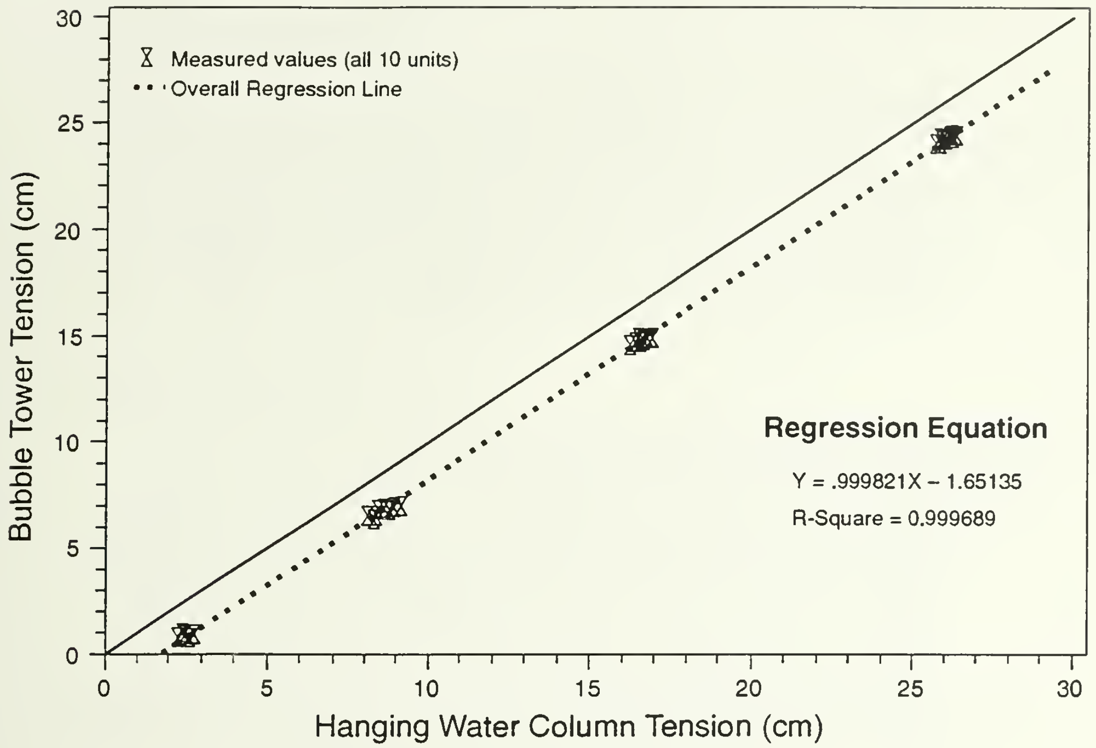

Figure 4. Summary plot of bubble tower tension versus hanging water column tension for all 10 Soilmoisture TI units. The crosses are the individual measurements and the broken line is the regression through the data. The solid line is the 1:1 line.

in their response, and this response is highly linear over the full range of tensions. The non-zero regression intercepts indicate, however, that the bubble towers underestimate the actual tension on the porous disk by an average of 1.65 cm. That is, the actual tension on the base of the porous disk is, on average, 1.6548 (± 0.1818) cm greater than indicated by the bubble tower (Table 2). Probably the best way to account for this "offset" is to place a 1.65 cm layer of contact sand between the porous disk and the soil (Fig. 1). This makes the tension at the soil surface equal to the tension indicated by the bubble tower, and simultaneously ensures good hydraulic contact between the porous disk and the soil. Recommendations regarding the type of material to use as a contact sand and how it might be placed are given in Reynolds (1993).

The hanging water column tensions tended to oscillate approximately ± 0.1 cm around the steady values. This oscillation was in phase with the bubbling of the bubble tower, and was therefore probably the result of pressure pulses caused by the breaking bubbles. The laboratory resolution of the bubble towers therefore appears to be about ± 0.1 cm. This resolution probably drops to around ± 0.5 cm in the field, due to additional disturbances such as wind, solar heating, irregularities in the soil surface, and the accuracy with which the contact sand can be placed.

6. Maintenance of the Porous Disk

Over a field season of continuous use (say, 4 months), the Ksat of the porous disk may gradually decline due to the progressive accumulation of algal/mould growths (these appear as green and grey patches on the disk) and iron/aluminum precipitates (red and brown patches). These accumulations can be removed by soaking the disk for about 24 hours in concentrated bleach solution (30% by vol. commercial bleach, 70% by vol. distilled water) to remove the algae and moulds; and then soaking again (after flushing out the bleach) for about 48 hours in dithionite-citrate solution (0.4 g dithionite per 25 ml of 0.68 M sodium citrate solution) to remove the iron/aluminum precipitates. This treatment also removes the chemical wetting agent, however, and the disk must consequently be re-treated with surfactant to re-establish its wettability. The disk may have to be removed from its aluminum support and retaining rings (Fig. 2, 3) before cleaning, as bleach tends to react with unanodized aluminum.

7. Comments Concerning Field Operation

On some of the TI units, the support tube tended to pull out of the foot cover when the TI was full of water due to slippage of the O-ring connection (Fig. 2). It would consequently be advisable to develop a means for locking this connection when using the TI in the field. It is also felt that the bubble tower (i.e. marriot bubbler assembly, Fig. 2) should be protected with some form of brace or shield during field operation, as its connection to the foot cover appears somewhat fragile.

If the TI is not level, air bubbles from the marriot bubbler assembly (bubble tower) may accumulate under the foot cover, rather than entering the support tube and rising up into the reservoir (Fig. 2). This situation should be avoided, as it introduces error into the infiltration rate measurements.

8. Recommendations

Although only laboratory testing of the Soilmoisture TI's has been performed at this writing, it nevertheless appears that they will perform well in the field providing that certain precautions are taken and procedures followed. These include:

i) periodically treating the porous disks (perhaps every 2–4 months) with a chemical surfactant to establish and maintain maximum wettability and Ksat.

ii) periodically cleaning the porous disks (perhaps every 4 months of continuous use) to remove growths and precipitates and thereby re-establish maximum Ksat.

iii) not attempting to use the TI outside of its K(h) range (approx. 10^{-6} cm/s $\leq$ K(h) $\leq$ 3 x 10^{-3} cm/s).

iv) periodically testing for air leaks in the seal between the porous disk and the support ring, and installing a retaining ring (Fig. 3) if necessary.

v) compensating for the 1.65 cm tension offset (underestimate) of the bubble tower, preferably by placing a 1.65 cm thick layer of contact sand between the porous disk and the soil surface.

vi) following the general procedures and guidelines for field use of TI's recommended by Reynolds (1993), Ankeny (1992), Elrick and Reynolds (1992) and White et al. (1992).

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