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Development and Preliminary Evaluation of an Improvised Tension Disc Permeameter for Determining Unsaturated Soil Hydraulic Properties

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Abstract

An improvised tension disc permeameter for determining the unsaturated hydraulic properties of soil was fabricated using low-cost and locally-available materials. The functionality of the equipment was evaluated by quantifying on-site infiltration parameters at three applied tensions: 5, 10, and 15 cm. The infiltration data, together with the volumetric moisture content, were used to estimate the soil's sorptivity and unsaturated hydraulic conductivity. Results from 15 infiltration runs at the experimental site yielded average sorptivity and unsaturated hydraulic conductivity estimates of the silty clay loam soil equal to 0.0846 mm/s$^{0.5}$ and 0.0441 mm/s, respectively. Consistency of results with theory shows that the equipment can reliably estimate soil hydraulic properties in the absence of sophisticated instruments.

Keywords: Tension disc permeameter, sorptivity, unsaturated hydraulic conductivity, volumetric moisture content, infiltration

Introduction

The quantification of the hydraulic properties of soil is an important requisite to the application of engineering solutions to various problems such as irrigation, drainage design, optimization of crop yield, and erosion control. Soil hydraulic properties describe the retention and transmission of moisture in soil and are vital for predicting how water will flow within and drain from it.

Two particularly important soil hydraulic properties are sorptivity (S) and hydraulic conductivity (K). Sorptivity is the measure of the capacity of soil to absorb or desorb water by capillary action alone, exclusive of gravitational effects (Philip, 1969). In turn, hydraulic conductivity is the quantitative measure of the ability of soil to transmit water (Minasny & George, 1999), and is generally of two types – saturated or unsaturated – depending on the state of moisture saturation of soil. On one hand, field-saturated hydraulic conductivity (K_{fs}) is the rate of water movement through soil when it has been brought to a saturated state by applying water abundantly at the soil surface through ponded infiltration or during extreme rainfall events. On the other hand, unsaturated hydraulic conductivity $K(\theta)$ characterizes flow through an initially dry soil wherein macropores are filled with air, leaving only the finer pores to accommodate water movement. *K(θ)* is generally more difficult to measure, apart from the fact that it usually requires expensive instrumentation. As such, soil hydraulic conductivity measurements have often been focused on K_{fs}. Meanwhile, *K(θ)* is widely regarded as the most important property for studying water transmission and solute transport in porous media (Ghanbarian-Alavijeh & Hunt, 2012).

Among the various instruments used to measure water infiltration in soil, only the tension disc permeameter is capable of measuring *K(θ)*. A single unit of this instrument usually costs several thousand dollars which makes purchase impractical, as it is utilized only for brief periods and only occasionally.

Disc permeameters are useful in characterizing macropores, in quantifying and delineating spatial variations in surface infiltration, and in estimating hydraulic properties using numerical inversion method (Minasny & George, 1999). One of its advantages over other infiltration equipment is the ease by which both the K_{fs} and *K(θ)* may be estimated. Typically, a disc permeameter consists of a bubble tower which sets the tension at the bottom face of the disc, and a water reservoir which measures the soil infiltration. Its miscellaneous components include a nylon mesh contact layer and a disc made of sintered or porous material. As of writing, no report exists on *K(θ)* measurements of Philippine soils using disc permeameters.

In this study, we attempted to develop a tension disc permeameter prototype that provides estimates of unsaturated soil hydraulic properties in an experimental site. Specifically, we intended to (1) design and fabricate an improvised tension disc permeameter using low-cost and locally-available materials, (2) determine the sorptivity and unsaturated hydraulic conductivity of soil using the fabricated tension disc permeameter, and (3) evaluate the improvised tension disc permeameter based on other established design considerations.

Methodology

The criteria and physical elements that governed the design of an improvised tension disc permeameter from low-cost and locally-available materials were initially defined. The succeeding discussions describe the considerations for the design and the physical components that made up the equipment.

Design Considerations

Various design parameters such as equipment functionality, durability, ease of manufacture, and cost were considered in coming up with the improvised disc permeameter. Functionality was evaluated in terms of its ability to measure infiltration in soil. Durability of design was evaluated by observing the sturdiness of the individual components and the instrument as a whole before, during, and after every infiltration test. Ease of manufacture was evaluated based on the simplicity or complexity of the design itself. Finally, equipment cost was determined as the aggregate cost of the material components.

Design of the Improvised Equipment

The major components of the improvised tension disc permeameter are the water reservoir, bubble tower, and base frame or disc. The design was formulated in such a way that each of these components was made from inexpensive and locally-available materials. Table 1 lists the materials used for fabrication while Figure 1 shows the fabricated equipment.

Table 1. Materials used for the fabrication of the improvised tension disc permeameter.

COMPONENT	MATERIAL USED	SPECIFICATIONS
Major Components:		
A. Water reservoir	Plexiglass tube	Nominal diameter: 2”; Length: 36”
B. Bubble tower	Plexiglass tube	Nominal diameter: 1”; Length: 12”
C. Base frame or disc	Galvanized iron (GI) sheet; Flat bar; Couplings	GI sheet: 200 mm diameter; Flat bar: 1” x 1/8” x 26”; Couplings: 1 ½” and 1”inner dia.
Miscellaneous Components:		
D. Contact material	Cheesecloth and meshes	Diameter: 250 mm
E. Bubble entry tube	Glass tube	Inner diameter: ¼”*
F. Tube connecting the bubble tower to the reservoir	Silicon hose	Inner diameter: 1mm*
G. Scale to monitor the water reservoir level	Tape measure	Length: 1000mm*
H. Cork stoppers	Rubber stoppers	Inner diameters: 1 ¾” and ¾”

*Standard size

The improvised disc permeameter was designed following the typical structure of several commercially-available models, borrowing design elements where applicable or convenient. For example, the two cylinders comprising the two major components – water reservoir and bubble tower – were made of plexiglass tubes following the design of Perroux & White (1988). The two-inch and one-inch diameter of the reservoir and bubble tower, respectively, were based on Eijkelkamp’s (2010) Tension Infiltrometer. The manner of connection between these two cylinders was adopted from the hydraulic connection of Soilmoisture’s (2008) Tension Infiltrometer. The iron base disc followed Perroux & White’s (1988) standard disc diameter of 200 mm. Ordinary GI sheet was chosen as material for fabricating the iron base disc due to its affordability, availability, and ease to shape. A 1” flat bar, formed into a circular shape, was welded to the GI sheet disc and served as the base that supports the body of the permeameter.

The miscellaneous components of the improvised permeameter are the contact material, bubble entry tube, connecting tube, and cork stoppers. The contact material was made from layers of local cheesecloth and mosquito net which are a lot cheaper than the sintered metal disc used in Decagon’s (2015) Minidisk Infiltrometer and the nylon mesh fabric of McKenzie et al. (2002). A glass tube with an inner diameter of ¼” served as bubble entry tube. The connecting tube from the bubble tower to the reservoir was made from 1 mm silicon air hose used in aquaria systems. Lastly, rubber stoppers were fitted to the mouths of the two plexiglass tubes to secure air tightness.

Tension Disc Permeameter Setup

Close contact between the improvised instrument and the soil surface was maintained by selecting a relatively smooth, flat surface on the experimental site. A carpenter’s level was set on top of the disc to ensure that the permeameter stood perpendicular to the soil surface. Before conducting infiltration experiments, dry samples were obtained using core samplers (7.55 cm diameter, 7.35 cm height) for the measurement of bulk density ρ_b (M/L^3). Soil samples were brought to the laboratory for moisture analysis.

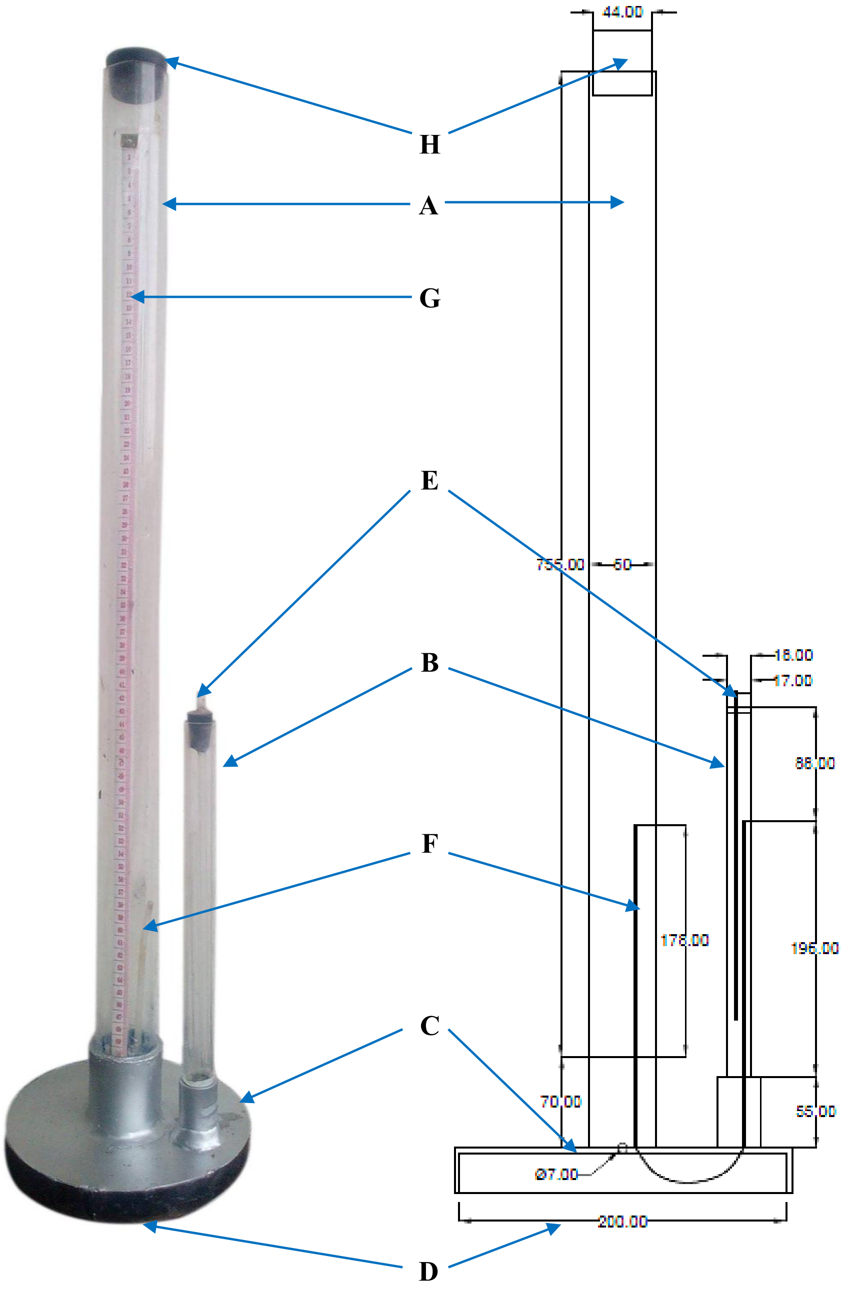

Figure 1. Actual (L) and schematic diagram (R) of the improvised tension disc permeameter. (*Note:* Refer to Table 1 for the corresponding component at each letter label. Label "D" only specifies the location of the contact material, as it is attached only during the conduct of infiltration experiments.)

The initial volumetric water content θ_i was determined using the equation below,

$$\theta_i = w_i \rho_b \qquad (Equation\ 1)$$

where w_i is the initial moisture content by mass (g/g).

Infiltration experiments were carried out at a specified tension h (Figure 2). A large interval among the tensions was considered so that explicit and conclusive relationships can be made between the applied tension and the soil hydraulic properties being estimated. Infiltration of water from the reservoir was signaled by the entry of air into the system through the entry tube in the bubble tower. The drop in water level in the reservoir was recorded as a function of elapsed time t until the soil had reached a steady rate of infiltration. The equipment was then removed from the soil surface and, using a core sampler, wet samples from the infiltrated surface were obtained to get the final volumetric moisture content θ.

A separate set of soil samples were subjected to hydrometer analysis to determine their particle size distribution. Corrections for viscosity due to temperature changes and soil density variability with the standard of 2.65 g/cm^3 were applied. A semi-logarithmic plot of the particle size diameter with the relative percentage of soil suspension was generated, and the resulting soil type of the sample was determined using the Atterberg chart. Identification of the specific soil type of the experimental site is required in determining empirical constants for the van Genuchten-Zhang method (Zhang, 1997) of estimating *K(θ)*.

Analysis of Tension Disc Permeameter Measurements

The drop in water level in the reservoir corresponds to a certain value of infiltration rate. The infiltration depth i at a certain time period was computed using the equation

$$i = \frac{q}{A} \qquad (Equation\ 2)$$

where i is the infiltration depth (mm), q is the amount of inflow (mm^3), and A is the disc area (mm^2).

Instantaneous $\boldsymbol{i}$ values were tabulated and successive points were added to obtain the cumulative infiltration $\boldsymbol{I}$. Infiltration curves showing the relationship between the square root of time $\boldsymbol{t^{0.5}}$ at the abscissa and cumulative infiltration $\boldsymbol{I}$ at the ordinate was derived from each trial. From the infiltration curve, the polynomial equation and coefficient of determination (R^2) were obtained. The polynomial equation was in the form $ax^2 + bx + c$. However, the value of c was neglected based on the simplified Philip's (1969) equation. The sorptivity S in mm/s$^{0.5}$ is given by the value of b and the steady-state infiltration rate A' in mm/s is obtained as the numerical value of a.

White et al. (1992) method (Equation 3) and van Genuchten-Zhang method (Equation 4) were used to obtain unsaturated hydraulic conductivity estimates from the infiltration data. The equations employed for these methods are provided below:

$$K(\theta) = Q_\infty - \frac{4bS^2}{\pi r_0(\theta - \theta_i)} \qquad (Equation\ 3)$$

$$K(\theta) = \frac{C_2}{A} \qquad (Equation\ 4)$$

where:

Q_∞	is the steady-state infiltration rate (L/T)
b	is the shape factor for soil water diffusivity function equal to 0.55 for field soils
S	is the sorptivity (L/T$^{0.5}$)
r_0	is the effective radius of disc (L)
θ	is the final volumetric moisture content (L^3/L^3)
θ_i	is the initial volumetric moisture content (L^3/L^3)
C_2	is the steady-state infiltration rate (L/T)
A	is the value relating the van Genuchten parameters for a given soil type to the tension and radius of the infiltrometer disc which is given by these equations:

$$A = \frac{11.65\left(n^{0.1}-1\right)\exp[2.92(n-1.9)\alpha h]}{(\alpha r_0)^{0.91}} \quad \text{when } n \geq 1.9 \qquad (\textit{Equation 4a})$$

$$A = \frac{11.65\left(n^{0.1}-1\right)\exp[7.50(n-1.9)\alpha h]}{(\alpha r_0)^{0.91}} \quad \text{when } n < 1.9 \qquad (\textit{Equation 4b})$$

where:

n, α are the van Genuchten parameters dependent on the soil type

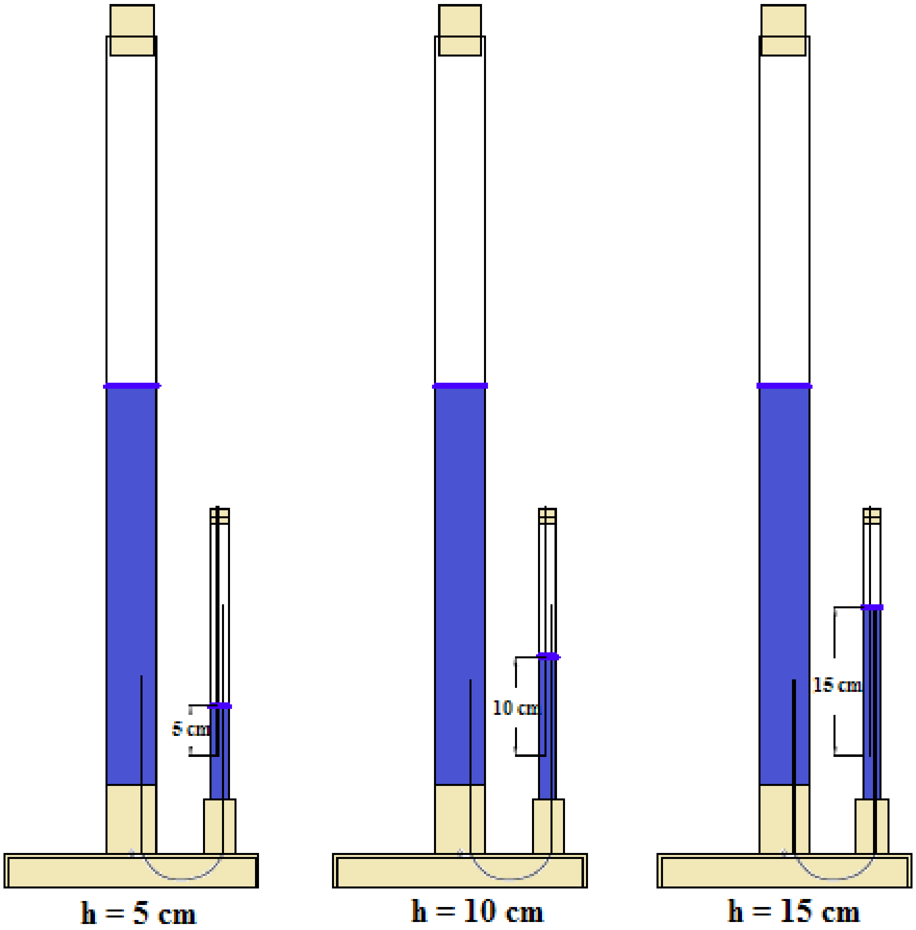

Figure 2. Water levels maintained at the bubble tower at the application of three individually applied tensions.

Results and Discussion

Soil Physical Properties

Field estimation of *S* and *K(θ)* from infiltration measurements requires determination of some soil physical characteristics. These soil physical properties such as soil type, bulk density $\boldsymbol{\rho}_b$, and moisture content can influence the entry of water into the soil surface and its transmission within soil pores. Thus, measurement of these physical properties before and after every infiltration experiment is essential.

Soil in the experimental site was 13.30% sand, 57.60% silt, and 29.03% clay which correspond to a silty clay loam texture. Knowledge of the soil type in the experimental site is essential, as most soil properties and processes are dependent on it. In particular, it is necessary in analysis when using the van Genuchten-Zhang method (Zhang 1997). The initial volumetric water content θ_i was 0.1490 cm^3/cm^3. Final volumetric water contents are summarized in Table 2.

Table 2. Final volumetric moisture contents determined after each infiltration trial.

PROPERTY	TRIAL	TENSION (cm)		
		5	10	15
θ (cm^3/cm^3)	1	0.2603	0.4782	0.5977
	2	0.4334	0.5052	0.5530
	3	0.4512	0.5447	0.5282
	4	0.2560	0.5044	0.5283
	5	0.4034	0.5672	0.4968
AVERAGE		0.3609	0.5199	0.5408

Results show that, in general, final volumetric moisture contents increase with increasing tension. This observation is consistent with infiltration theory models such as the van Genuchten-Zhang equation which shows the direct relation between infiltration rate and tension. Deviations from this expected outcome may be attributed to some variability in soil composition within the test site itself.

Disc Permeameter Manometry

The pressure distribution of the two fluids (Figure 3) inside the system during infiltration experiments was analyzed to determine whether fluid elevation affected the resulting pressure of the system. To facilitate the analysis, a simplified manometer diagram representing the system was developed (Figure 4) from which the change in pressure of the system can be determined as

$$\Delta P = P_{atm} + \gamma h_{BT} + \gamma h_{air,1} - \gamma h_{WR} - \gamma h_{air,2} \qquad (Equation\ 5)$$

where:

ΔP	is the difference in pressure (L)
P_{atm}	is the atmospheric pressure equal to 1019.744 cm H_2O
γ	is the specific weight of the fluid present ($ML^{-2}T^{-2}$)
h_{WR}	is the water level in the reservoir (L)
h_{BT}	is the water level in the bubble tower (L)
$h_{air,n}$	is the height of the space occupied by air (L) in the connecting tube (*1*) and water reservoir (*2*)

The simplified manometer diagram illustrates the arrangement of fluids in the system, starting from the bubble tower up to the air enclosed in the upper portion of the water reservoir.

The value assigned to h_{BT} was based on the maintained tension (5, 10, or 15 cm) in the system during the infiltration trials. A lower applied tension (refer to Figure 2) corresponds to a greater air pressure maintained in the bubble tower. On the other hand, the value of h_{WR} was measured when the initial reservoir level was at the zero position in the measuring tape and when it was set to a lower height corresponding to the 15 cm position. Substitution of the measured air and water levels to Equation 5 provides insight into the effect of air pressure in the bubble tower on the rate of flow inside the water reservoir.

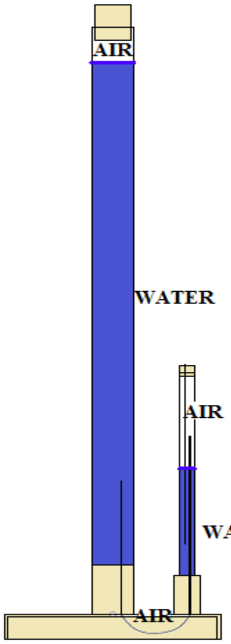

Figure 3. A diagram of the equipment showing the fluids present.

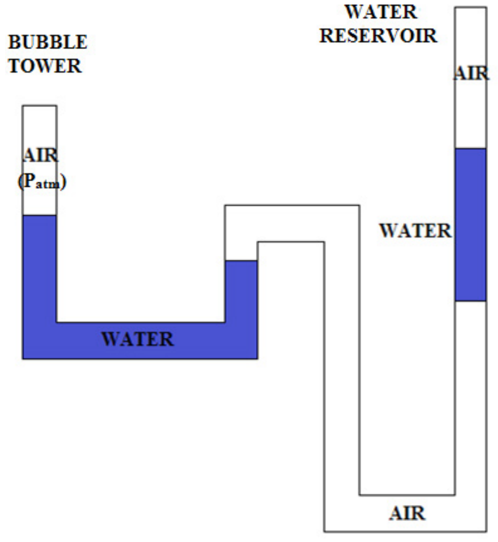

Figure 4. A simplified manometer to illustrate the arrangement of fluids in the system.

Table 3 shows the average of individual pressure differences (Δ*P*) at different tension levels computed when the initial water level in the reservoir is at 0 cm and when it is lowered to 15 cm. The values of Δ*P* at different water levels in the bubble tower primarily derive from atmospheric pressure and appear to vary only slightly. The same can be said with values of Δ*P* when the water level in the reservoir is changed from 0 cm to 15 cm. As such, it can be inferred that changes in the elevation of the two fluids does not greatly affect the resulting pressure of the system. This means that, when conducting field experiment using the improvised tension disc permeameter, the initial water level in the reservoir can be set to any height without having to worry about considerable effects on the pressure distribution inside the equipment and on infiltration measurements.

Table 3. Average pressure difference (Δ*P*) at three tensions.

TENSION (cm)	Δ*P* when h_{WR} is at 0 cm initial level (cm H_2O)	Δ*P* when h_{WR} is at 15 cm initial level (cm H_2O)	AVERAGE Δ*P* (cm H_2O)
5	960.2487	975.0032	967.6259
10	965.1733	979.9277	972.5505
15	970.0978	984.8523	977.4751
AVERAGE	965.1733	979.9277	972.5505

Evaluation of the Fabricated Tension Disc Permeameter

The four design considerations evaluated were functionality, durability, ease of manufacture, and cost. Functionality of the equipment was evaluated by (1) directly observing the reduction in water level at the reservoir through time, and (2) conducting actual infiltration experiments in the field. The first procedure was deemed necessary to inspect for factors other than soil infiltration that may affect the rate of water reduction in the reservoir.

The functionality of the tension disc permeameter rests largely upon the ability of the water reservoir to provide water for infiltration into the soil surface. Meanwhile, the bubble tower serves to impose and maintain constant tension at the cloth base throughout the infiltration process. Infiltration was measured by the lowering of the water level in the reservoir (Figure 5) at a specified tension set at the bubble tower. To establish the functionality of the equipment, two setups were compared – one *without* soil surface contact and the other *with* soil surface contact.

Table 4 shows the change in the water level inside the reservoir with the equipment having no soil surface contact and the actual infiltration data obtained in the field where the equipment is placed in contact with the soil.

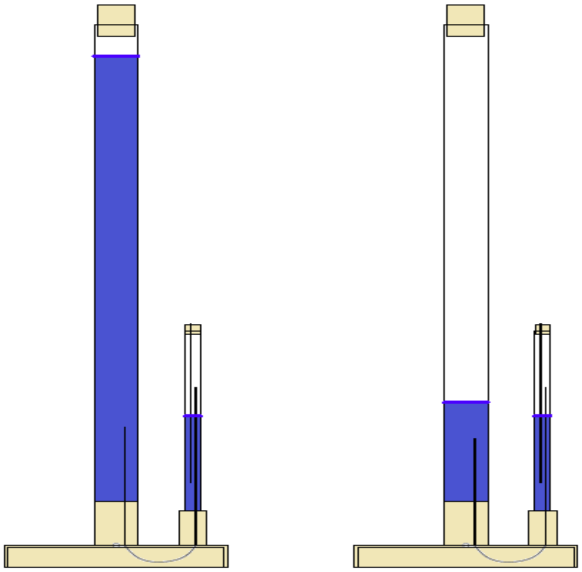

Figure 5. The tension disc permeameter setup showing the change in water reservoir level from $t = 0$ (left) to $t = t_f$ (right).

Table 4. Water level drop in the reservoir *without* and *with* soil surface contact.

ELAPSED TIME (seconds)	WATER LEVEL (cm)					
	5 cm		10 cm		15 cm	
	without	with	without	with	without	with
0	3.0	7.0	13.0	2.5	5.1	12.0
15	3.8	9.0	14.0	3.7	6.2	13.3
30	4.6	10.5	15.0	6.0	7.3	15.6
45	5.4	12.0	16.1	7.1	8.4	16.7
60	6.6	13.7	17.5	8.5	9.7	18.0
75	7.8	15.4	18.7	9.8	11.7	19.3
90	9.0	17.1	20.6	10.7	13.8	20.6
105	10.5	18.8	21.8	12.1	14.9	21.9
120	12.0	20.5	23.4	14.5	17.0	23.2
f-statistic	5.05		28.45		15.54	
f-critical, $\alpha = 0.05$	4.45					

As may be observed from Table 4, a slower drop in water level occurred when infiltration runs were conducted on a flat, smooth, concrete surface than when the equipment was in actual contact with the soil surface. Analysis of variance at a significance level $\alpha = 0.05$ confirms that at all applied tensions, the water level drops in the two infiltration runs are significantly different from each other. Mounting the base frame disc onto a non-porous surface restricted the flow of water from the reservoir. On the other hand, mounting the base frame disc on soil permitted flow of water from the reservoir. These observations suggest that the improvised equipment functions as intended.

Data from Table 4 also suggests that the rate of water drop in the reservoir may have been influenced by some components of the improvised equipment. For example, sudden drops in water level at the onset may be attributed to the oversized center hole at the equipment's bottom mouth lid. The diameter of the center hole was dictated by the diameter of the side-tube hole which provides the hydraulic connection between the bubble tower and reservoir. Meanwhile, the size of the side-tube hole was dependent on the outer diameter of the standard silicon hose to be fitted to it. As such, some imperfections on the performance of the improvised equipment may be ascribed to limitations inherent to locally-available materials.

Evaluation of the soil infiltration data in Table 4 reveals that the drop in water level at the early stage of infiltration can be attributed to pore spaces getting filled with water and air being displaced. As infiltration proceeds, the drop in water level slows down and eventually reaches steady-state. A representative infiltration curve is presented in Figure 6.

To compare soil infiltration characteristics as a consequence of the three individually applied tensions, infiltration curves were plotted and are presented in Figure 7. It is evident from the graph that as time progresses, cumulative

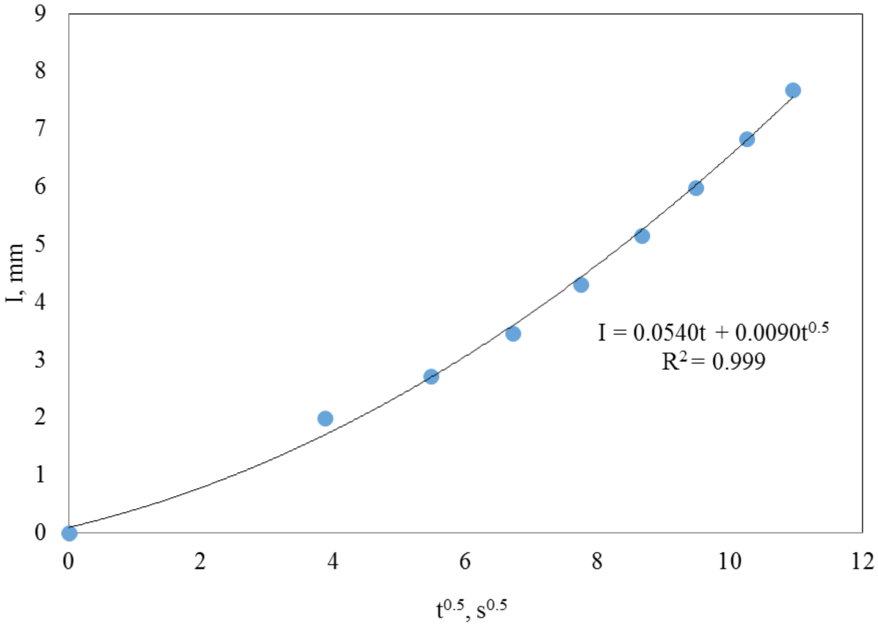

Figure 6. A sample infiltration curve generated.

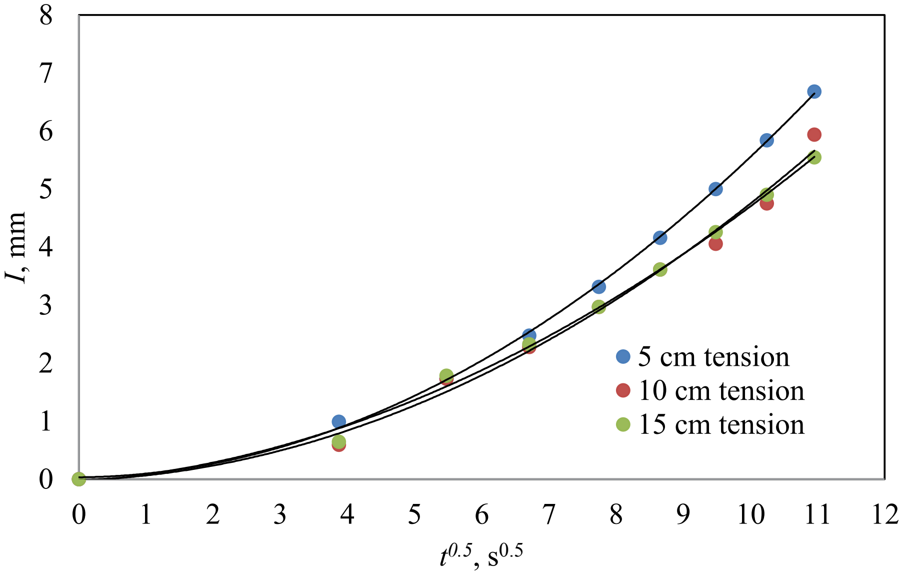

Figure 7. Infiltration curve at applied tensions of 5, 10, and 15 cm.

infiltration ***I*** decreases with increasing applied tension. This may be explained by the fact that the greater the tension applied, the smaller are the maximum pore sizes that can participate in flow from the soil surface that results in lower infiltration volume (Minasny & George, 1999; Perroux & White, 1988). With the relationship among the actual measurements using the improvised disc permeameter matching those described by established theories, the design was considered functional despite some imperfections of the components.

The durability of the equipment was assessed by inspecting the whole assembly before, during, and after each operation. Initially, the bubble tower was not fixed in the assembly (adopted from Soilmoisture's Tension Infiltrometer) to easily control the water level when setting tension values. Also, the contact layer was detachable and was set to place only during the conduct of experiments. After several rounds of assembly and disassembly, the entire equipment was observed to remain sturdily fixed when the various components are put together for reuse. With this observation, the improvised equipment was deemed practically durable.

Manufacture of the equipment was determined to be relatively easy, as the design was adopted from existing models and with simplifications added. Finally, the cost of materials for the fabrication of the equipment was estimated to be approximately Php 2,200 (US$ 50). Compared to the most affordable tension disc permeameter in the global market (Decagon's Minidisk Infiltrometer), the improvised equipment is at least 20 times cheaper.

Soil Hydraulic Properties

The soil sorptivity and unsaturated hydraulic conductivity measured using the improvised equipment is presented in Table 5. Results obtained using White et al. (1992) analysis showed dominance of Q_∞ on the estimates of $K(\theta)$. The ratio of S to the difference in moisture contents, $(\theta - \theta_i)$, was very small as to substantially affect the value of $K(\theta)$. Thus, the steady-state infiltration rate alone can be considered as the estimate of $K(\theta)$ obtained from using the fabricated equipment.

Using results from 15 infiltration runs, S and $K(\theta)$ of the silty clay loam at the experimental site was estimated to be 0.0846 mm/s$^{0.5}$ and 0.0441 mm/s, respectively.

Table 5. Soil sorptivity and unsaturated hydraulic conductivity.

TENSION (cm)	S (mm/s$^{0.5}$)	$K(\theta)$ (mm/s)	
		White	van Genuchten-Zhang
5	0.0372	0.0536	0.0210
10	0.0554	0.0412	0.0126
15	0.1612	0.0375	0.0090
AVERAGE	0.0846	0.0441	0.0142

In theory, steady-state infiltration rate and sorptivity are interdependent, and their values influence the unsaturated hydraulic conductivity estimate (White et al., 1992). Implied in this method is the assumption of similarity between capillary forces acting to draw water into the soil when steady-state flow is achieved and those at the onset of infiltration (Cook & Broeren, 1994). In contrast, estimates of $K(\theta)$ obtained from the van Genuchten-Zhang method are much lower compared to those obtained using White et al. (1997) method. This discrepancy can be attributed to the large value of the van Genuchten parameter A which increases as tension is increased. For this reason, estimates of $K(\theta)$ using the White et al. (1997) method are deemed more reliable.

Conclusion

An improvised tension disc permeameter was developed using low-cost and locally-available materials. The functionality of the equipment to estimate unsaturated hydraulic properties was tested and evaluated by quantifying the infiltration characteristics of a silty clay loam soil at three applied tensions: 5, 10, and 15 cm. Using infiltration data generated, the sorptivity S and unsaturated hydraulic conductivity $K(\theta)$ of the soil were determined.

It was found that the pressure difference in the system is only slightly affected by applied tension and initial water level in the reservoir, which means that water levels can be varied liberally without causing substantial discrepancies and inaccuracies on infiltration results. Upon evaluating the equipment based on design considerations, the improvised tension disc permeameter was considered functional despite some imperfections brought about by limitations inherent to the material resources. The equipment was also determined to be economical, durable, and easy to manufacture.

Further improvement and modification of the components making up the connection between the two cylinders is desired to accommodate longer infiltration runs. It is likewise recommended to use an actual tension disc permeameter or the more practical constant head Mariotte bottle experiment on the same site to validate the estimated hydraulic properties.

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