IMPROVEMENT OF A SIMPLE TENSION INFILTROMETER FOR DETERMINING SOIL HYDRAULIC PROPERTIES

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ABSTRACT

An improved design of an existing simple tension infiltrometer which could use easily available PVC pipes for its water reservoir is presented. The disc is made of cast aluminium and incorporates a reservoir pipe adapter to facilitate the use of multiple reservoir pipe sizes. The test results from the constructed infiltrometer in loamy sand showed the performance of the equipment to be consistent and satisfactory suggesting that the equipment would be useful in routine research instrumentation and sturdy enough for use in students' practical works. It was considered valuable in our local situation where typically there are resource constraints for importing sophisticated instrumentation and components.

Keywords: Hydraulic conductivity, sorptivity, tension infiltrometer design.

INTRODUCTION

A tension infiltrometer enables soil infiltration measurement at negative potentials which prevent preferential flows through cracks, root holes and worm holes. Thus, it ensures more accurate determination of hydraulic properties of the soil matrix near saturation than would have been the case if a ponded ring infiltrometer was employed. Sorptivity and hydraulic conductivity are two hydraulic properties that could be determined from the infiltration measurements. Hydraulic conductivity relates to the ability of the soil to transmit water through the soil mass while sorptivity indicates the capacity of the soil matrix to absorb water during the early stages of infiltration when the effect of gravity is negligible and the process dominated by the sorption of water into the soil matrix. Knowledge of soil hydraulic conductivity and sorptivity is essential in hydrological, agronomic and soil water conservation studies requiring the simulation of soil water flow.

Clothier and White (1981) pioneered the development of the tension infiltrometer while Perroux and White (1988) established a design procedure for the system. Different designs and adaptations have since been proposed by several researchers to address specific measurement problems. For example, in order to reduce the pressure on the soil surface due to the weight of the equipment, Casey and Derby (2002) developed a tension infiltrometer having the bubble tower and the water reservoir assembly as a unit separate from the disc. Flexible tubes were used for the hydraulic and pneumatic connection of the units. Monitoring and recording were automated with differential pressure tranducers and a data logger. In an attempt at eliminating the need for a contact material between disc and the soil surface, Schwarzel and Punzel (2007) designed a tension infiltrometer with disc in form of a hood. The disc, water reservoir and manometer for regulating water potential were separate units which were interconnected with flexible tubes. The tensiometers with separated discs are however not easy to set up for quick field measurements. The relative elevation between the disc surface and the air entry point of reservoir and bubble tower assembly need to be properly monitored for accurate setting of the water potential at the disc surface. Castiglione *et al*. (2005) developed a tension infiltrometer only suitable for measuring infiltration into fractured rock at very low flow rates. Temperature-compensated pressure transducers, solenoid valves, and a data logger were incorporated for automated control and data acquisition. An automated refill system was also included to facilitate unattended operation for long equilibrium periods typical in infiltration experiments on unsaturated fractured rock.

The difficulties in local adaptation of the existing designs due to the high cost fabrication materials which are not readily available have been highlighted by Ejieji and Yusuf (2007). They therefore presented two simple designs which, instead of the usual practice of using only perspex plastic for all the major components, could essentially use easily available galvanised iron sheet and polyvinyl chloride (PVC) pipe, that is, the PVC pipe commonly used for domestic piping of water and effluents. The disc, water reservoir and bubble tower were assembled as a unit. The equipment could be set up easily to facilitate quick measurements. Field application of their devices constructed from the designs was demonstrated with results from *in-situ* infiltration tests. The major shortcomings of their device include the use of thick-guage transparent polythene sheets to cover the observation slits on the water reservoir. The polythene covering tended to collapse inwards during operation due to the sub-atmospheric pressures in the tensiometer. Thus, the internal cross sectional area of the water reservoir and therefore the sensitivity factor of the equipment (that is, the ratio of the effective cross sectional area of the disc to internal cross sectional area of the water reservoir) could alter during operation. The polythene sheet also tended to soften under high air temperatures in the field thereby increasing the risk of accidental puncture. No provision was made for the use of multiple reservoir pipe sizes on the disc. In effect, a new disc would be required each time test conditions require the alteration of the reservoir pipe size.

The objectives of this paper therefore are to present a design which addressed the limitations of that of Ejieji and Yusuf (2007) and to demonstrate the application of the device constructed from the design with experimental results.

DESCRIPTION OF THE INFILROMETER

The details of the improved infiltrometer are shown in Figures 1, 2 and 3. The main components of the infiltrometer are the disc, the water reservoir and the bubble tower. The design guidelines of Perroux and White (1988) were mainly followed in sizing the components.

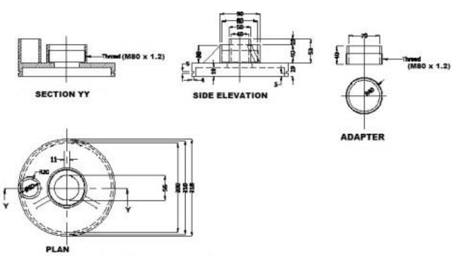

Figure 1. Details of the cast aluminium disc of the tension infiltrometer

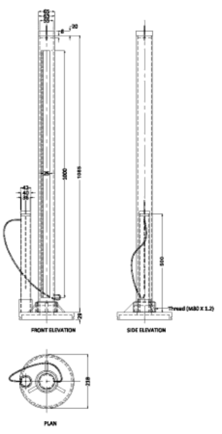

Figure 2. Details of the complete tension infiltrometer (membrane and its fastener not shown but linen scale attached to left side of the 25 mm slit is shown in the front elevation).

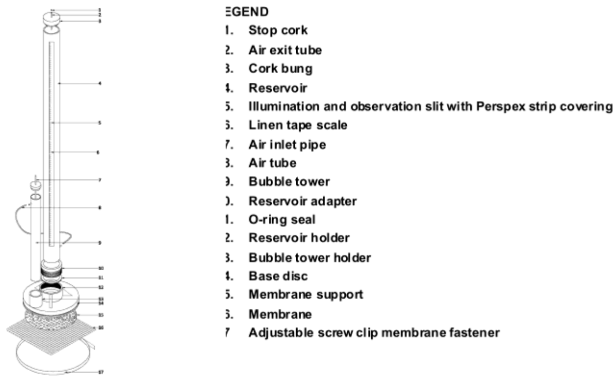

Figure 3. Isometric projection of the tension infiltrometer with the components shown in exploded view.

The new disc was fabricated from cast aluminium instead of sheet metal (Figure 1) The disc is 29 mm high with internal and external diameters of 200 mm and 218 mm respectively. The 200 mm internal diameter is the effective diameter for water infiltration and was considered adequate based on experiences reported in literature (Perroux and White, 1988; Cook and Broeren, 1994; Wyseure *et al.*, 1997). At the top of the disc, offset towards the edge, is the bubble tube holder while the water reservoir holder is centrally located and has an internal thread for screwing in the water reservoir pipe adapter. The adapter has internal and external diameters of 65 mm and 80 mm respectively. It is threaded externally for screwing into the reservoir holder with the lower end pressing to the bottom of the reservoir holder against an O-ring seal made from medium density plastic foam material (the O-ring seal is shown in Figure 3). The pipe adapter allows for the possible use of more slender water reservoir pipe sizes to increase sensitivity of infiltration measurements in slowly permeable soils. The design of Ejieji and Yusuf (2007) had no provision for an adapter.

At the lower end of the disc (Figure 1.), at an edge distance of 5 mm, is an external groove 5 mm wide and 4mm deep for placing a rubber seal against which the disc membrane is fastened. At the inner rim of the low end of the disc is a recess 1 mm deep and 1 mm wide (not shown in the Figures.) which holds the membrane support consisting of a 1 mm thick circular aluminium plate 202 mm in diameter and drilled all over with 2.5 mm diameter holes at about 5 mm centres for easy passage of water (Figure 3). The recess into which the membrane support sits obviates the need in Ejieji and Yusuf (2007) for a spacer between the membrane support and top underside of the disc thus reducing the number of disc components. The membrane which is made of nylon fabric (Ejieji and Yusuf, 2007) is stretched over the under face of the disc and held tightly to the side by a band of 12 mm wide iron strip bearing an iron screw-lock fastener at ends (Figure 3). To ensure air-tight sealing, the inside face of the band was lined with rubber band 12 mm wide. Thus, throughout the circumference of the disc, the membrane was held to the side of the disc between two bands of rubber.

The water reservoir 1085 mm long having internal and external diameters of 58 mm and 63 mm respectively was made from a PVC pipe (Figure 2). The length was such that the portion spanned by the observation and illumination slits could hold 2.64 l of water which was considered adequate for the most demanding test scenario envisaged. Such scenario is in a dry very porous sandy soil formation. The two slits, in opposite sides of the pipe, were 25 mm wide and 1000 mm long at 50 mm edge distance from the top. Each slit was covered which a strip of perspex plastic which was first heat-treated and formed to the curvature of the pipe surface before being glued over the slit with PVC glue. The covering overlapped the slit opening by 10 mm right round. This rigid covering was an improvement to the approach of Ejieji and Yusuf (2007) where the reservoir was wrapped around with transparent thick-guage plastic sheeting to cover the slit. The plastic sheeting tended to collapse inward during operation due to the internal negative pressures of the infiltrometer. The upper end of the water reservoir was sealed with a plastic cork having an air outlet tube passing through the centre. The top end of the air outlet tube remains closed with a stopper when the infiltrometer is in operation. To ensure an air-tight connection, the lower end of the reservoir was lined with gas thread tape before being forced to fit into the adapter. The thread tape was also applied to the adapter thread before screwing into the reservoir holder.

The bubble tube was made from a perspex tube with a closed at the lower end. The top end was closed with a stop cork having an air inlet pipe, 500 mm long and 4 mm in internal diameter, passing through the centre. The air outlet of the bubble tower and the air inlet of the reservoir each consisted of a pipe 4 mm in internal diameter projecting 35 mm outwards from a hole at the side. The distance from the centre of the hole at the side of the bubble tower to the top is 60 mm. When assembled with the O-ring in place, the distance from the bottom face of the disc to the centre of the hole in the side of the reservoir was 115 mm.

A flexible 4mm diameter plastic tube the ends of which were forced to fit the air outlet and inlet pipes were used for the pneumatic connection between the bubble tower and the water reservoir. The connections to the air pipes were further secured with metal clips. The pipes for the air inlets and outlet were fabricated from transparent plastic casings of ball point pen. The adequacy of the sizes of the pneumatic connections for the maintenance of acceptable airflow rates for short infiltration times was verified using the equation of Perroux and White (1988) which can be stated as in Equation (1).

$$r = \left\{ \frac{4\eta R^2 S t^{-\frac{1}{2}} l}{(Z_1 - \varphi_0)\rho_w g} \right\}^{\frac{1}{4}} \qquad (1)$$

where r is the radius of the connecting tube, l is the length, η is viscosity of air, R is the effective disc radius, S is sorptivity, t is the time, φ_0 is the water potential at the soil surface, ρ_w is density of water, g is acceleration due to gravity, and Z_1 is the distance from the centre of the air inlet hole of the reservoir to the bottom face of the disc (0.115 m in this study). The design maximum values of S and φ_0 were 10^{-3} m $s^{-½}$ and 0.0 m H_2O respectively, l was 0.5 m while ρ_w and g were taken to be 1000 kg m^{-3} and 9.81 m s^{-2} respectively. The η-value adopted was 1.92×10^{-5} Pa s (Massey, 1975), being air viscosity at the assumed maximum operating air temperature of 40 ^oC outdoors. For the first 1s of infiltration considered the most critical time interval, the estimated value of r was 1.36×10^{-3} m. This implies that the 4 mm diameter for the size of the pneumatic connections was generous. It is also consistent with the suggestion of Perroux and White (1988) that air tube diameter size of 3 to 4 mm was adequate for a tension infiltrometer with effective disc diameter of 200 mm.

TEST PROCEDURE

Testing essentially involved checking to ensure that all the connections and sealing of the slits were air-tight. For this, the bubble tower was two-third filled with water and the cork bearing the air inlet pipe put in place. The air inlet pipe was thereafter closed with a cork. The infiltrometer was then placed in a basin containing water to a level below the top of the holders of the bubble tower and reservoir. The cork of the air outlet pipe of the reservoir was removed and suction applied to draw water into the reservoir to a level higher than the top end of the observation and illumination slits after which the cork was quickly replaced. The infiltrometer was then placed on level wet porous matting. The equipment was considered air-tight if bubbling of air was not observed in the reservoir and bubble tower with the plug of the air inlet pipe in place. Also, when the inlet pipe plugged, the water level in the reservoir is expected to remain steady. Unless there was air leakage, the water level was expected to fall only when the air inlet pipe was unplugged. Once the equipment was ascertained to be air-tight, trial infiltration test runs were conducted before actual experiments.

APPLICATION

The tension infiltrometer was used to perform infiltration tests in improvised soil bins. Each bin consisted of a plastic basin 360 mm in diameter and 180 mm deep. Soil in a fallow field near the Department of Agricultural Engineering and Biosystems Engineering, University of Ilorin was collected from 0 – 15 cm depth. The soil belongs to the order of alfisols -Tropeptic Haplustalf, (Soil Survey Staff, 1998). The soil sample was taken for textural analysis by the hydrometer method after which each bin was three-quarter filled with moistened soil. The filling was carried out in steps. For this, a layer of loose soil 10 cm thick was added at a time and moderately compacted using a wooden rammer. The bin was left in the sun after filling until the soil was air-dry. Whenever rainfall was imminent, the bin was covered with plastic sheeting. In this way the antecedent soil wetness was controlled before infiltration tests.

Two tests were conducted at each potential of -0.01m, -0.04m and -0.09m H_2O . The test potential was set using Equation (2) (Perroux and White, 1988)

$$\varphi = Z_2 - Z_1 \quad (2)$$

where φ is the water potential at the bottom face of the disc (m H_2O), Z_2 is the distance from the water surface in the bubble tower to the lower end of the air inlet tube (m) and Z_1 is as previously defined. Before each test, soil samples were taken for the determination of initial water content. Free-running sand was applied to provide a thin layer of good hydraulic contact material. The infiltrometer with the reservoir two-third full and the bubble tower half full of water was then carefully placed on the soil surface. The stop cork of the air inlet tube of the bubble tower was then removed to initiate water infiltration. Each test was continued until a steady-state infiltration rate was achieved. After each test a core sampler, 80 mm long and 80 mm in internal diameter, was used to obtain a sample for the determination of bulk density and final water content.

For each infiltration test, the cumulative infiltration was plotted against the square root of the time. Sorptivity determined as the slope of the straight portion of the early part of the plot. The plotting was only necessary for the identification of the straight portion. Actual estimation of sorptivity was carried out by linear regression analysis. The soil hydraulic conductivity was calculated using Equation (3) (White and Sully, 1987)

$$K = Q_\infty - \frac{4bS^2}{\pi R(\theta_i - \theta_f)}$$

(3)

where K is the hydraulic conductivity(m s^{-1}), Q_∞ is the steady-state infiltration rate (m s^{-1}), b is a constant with average value of 0.55, S is the sorptivity (m $s^{-½}$), R is the effective disc radius (0.10 m in this work), while θ_i and θ_f are, respectively, the soil initial and final water contents (m^3 m^{-3}).

RESULTS AND DISCUSSION

The experimental soil was composed of 84.6% sand, 6.4% silt and 9.0% clay. Using the textural triangle of Soil Survey Staff (1975) the soil was classified as loamy sand. The average initial soil water content before the infiltration tests was 0.01 m^3 m^{-3} and average bulk density was 1567 kg m^{-3}. The infiltration tests were unaffected by the bin boundaries because visual observation during the test showed that the spread of wetted soil did not reach the sides the bin and soils scooping immediately after the test revealed that the wetting front did not reach the bottom of the bin.

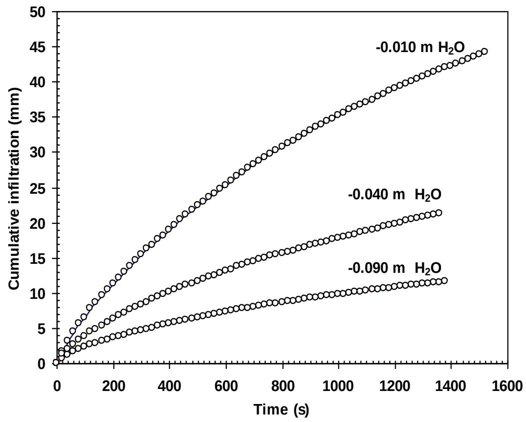

Figure 4. Typical cumulative infiltration versus time relationships obtained during infiltration tests at -0.90, 0.040 and 0.010 m H_2O potentials.

Figure 4 shows typical cumulative infiltration versus time relationships obtained during the infiltration tests. Average values of final soil water content (θ_f), sorptivty (S), steady-state infiltration flux(Q_∞), and hydraulic conductivity (K) determined at the various water potentials are presented in Table 1.

Table 1. Average values of final soil water content (θ_f), sorptivty (S), steady-state infiltration flux(Q_∞), and hydraulic conductivity (K) determined from the infiltration tests at the various water potentials (φ)

φ (m H_2O)	θ_f (m^3 m^{-3})	S (10^{-4} m $s^{-½}$)	Q_∞ (10^{-6} m s^{-1})	K (10^{-7} m s^{-1})
-0.090	0.188	3.75	6.25	3.40
-0.040	0.205	4.00	9.60	40.50
-0.010	0.269	4.40	15.00	94.50

The cumulative infiltration versus time relationships exhibited the expected gradation. They revealed that the higher the potential applied, the higher the cumulative infiltration observed. The same expected gradations were also evident in the results presented in Table 1where the values of θ_f, S, Q_∞ and K increased with soil water potential. The results have demonstrated the consistency of the infiltrometer which is comparable with that achieved by Ejieji and Yusuf (2007). The design presented here-in has however addressed the identified shortcomings of the infiltrometer critical to the reliability and durability. The cast aluminium disc has also fewer components. Unlike that the disc of the existing of infiltrometer, it would also be free from rust problems. Consistency would be better maintained in the new infiltrometer because of the improved features.

CONCLUSIONS AND RECOMMENDATIONS

An improved design of an existing simple tension infiltrometer has been presented. Like the existing one, it could use easily available PVC pipes for the water reservoir. In the new design, a cast aluminium disc with reduced number of components was used instead of one fabricated with sheet metal. A rigid perspex strip was used to cover the reservoir illumination and observation slits rather than transparent plastic sheet used in the existing design, thus improving the durability and operational reliability. A reservoir pipe adapter was also incorporated to facilitate the use of reservoirs having smaller diameters to increase sensitivity of measurement in slowly permeable soils. The test results from the constructed infiltrometer showed the performance of the equipment to be consistent and satisfactory. The outcomes are encouraging. The equipment would useful in routine instrumentation for research purposes. It is also sturdy enough for use in students' practical works. It would be valuable in our local situation where there are resource constraints for sophisticated instrumentation with imported components.

The infiltrometer would require regular checking for air leaks in order to ensure the reliability of measurements. To replicate the equipment for use, it is advisable to cast the disc carefully in order to eliminate porosities that would cause leakage of air. Further work on design improvements for automation is continuing.

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