*Journal of Nepal Geological Society, 1998, Vol. 18, pp. 249-258*

# Modified tension infiltrometer and its use to determine the unsaturated hydraulic conductivity of upper vadose zone

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## ABSTRACT

A modification of the CSIRO type tension infiltrometer was designed (designated UNCEL type) and tested. This infiltrometer is considerably cheaper, but more versatile, than any other infiltrometer reported so far. The modified infiltrometer was used in a reconstructed vadose zone to measure the unsaturated hydraulic conductivity and effect of compaction associated with the upper vadose zone.

Hydraulic conductivity, a function of matric potential, is a fundamental property for water entry into the soil as well as in the upper vadose zone. Tension ifiltrometer technique for determining unsaturated hydraulic conductivity, which is also a function of soil water pressure head, was compared with the existing techniques. The analysis of data from tension infiltrometer is based mainly on flow rate at steady-state condition. The steady-state measurement also enables to determine unknown parameters on the basis of at least two negative heads at the same location. This modified infiltrometer imposes pressure potentials at soil surface from 0.01 to 0.15 m of water, as a result macropores with an air entry value of less than applied tension are excluded. This is practictically useful when investigating the influence of structure and compaction of upper vadose zone.

Measurement of infiltration at various negative pressure head, with a single disc diameter allowed sensitive measurement of hydraulic properties of upper vadose zone with minimal surface disturbance. The newly designed tension inifltrometer and adopted schemes of calculation enable to determine unsaturated hydraulic conductivity of upper vadose zone with relevance to structural effects more accurately.

## INTRODUCTION

Hydraulic conductivity as a function of matric potential is the fundamental relationship for the analysis of water movement in soil as well as in the upper vadose zone. The upper vadose zone is commonly associated with hydrological processes such as infiltration, evaporation, groundwater recharge, soil moisture storage, and soil erosion (Costa, 1991). Most soil water interaction in the field occurs in unsaturated condition. Unsaturated flow processes are generally complicated since they often entail changes with variable soil wetness, tension (negative pressure head), hydraulic conductivity, compaction and arrangement of pore network. Presence of different macropores and preferential flow paths to field infiltration (Beven and Germann, 1982; Watson and Luxmore, 1986) has lead to a renewed interest in measurement technique in which preferential water flow through macropores and surface cracks are selectively controlled. One of the convenient ways to measure the unsaturated hydraulic conductivity of upper vadose is to apply water *in situ* at potential less than zero. The more negative the applied potential, the smaller the maximum diameter of pores that can participate in flow from the surface horizon (Perrox and White, 1988). A common limitation of such measurement is the availability of appropriate technique and reliable instruments. Most methods involve disturbance of the surface horizon of upper vadose zone, and as a result, damage the pore networks and do not reflects the real situation that prevail in the field. Because of the difficulty in obtaining representative undisturbed sample, *in situ* methods are potentially more accurate. In recent years, a new method and device (the tension infiltrometer) has been developed (Peroux and White, 1988; Ankeny et al., 1988; White et al, 1992; Jarvis and Messing, 1995) to measure the soil matrix properties *in situ*. The first proto type (the CSIRO tension infiltrometers) was developed by Perroux and White in 1988. It was difficult to control the tension at which infiltration occurred, not so robust, and not easy to carry the instrument in field. There remains a need of a tension infiltrometer that is portable when *in situ* field measurements are needed and allows easy, precise, control of infiltrating tension. In this paper, a modification of the CSIRO type tension infiltrometer is described. The aim of the modification is to make it cheaper and more convenient for field investigations. The modification has been tested in laboratory in relevance to variable compaction of a reconstructed upper vadose zone. Another objective is to quantify the contribution of various actively conducting pore-size classes and their fate due to the variable compactions.

## DIFFERENT TYPES OF TENSION INFILTROMETERS AND THEIR USES

The first simple tension infiltrometer for measuring the unsaturated flow properties of soils was developed by Perroux and White (1988). Ankeny et al. (1988) also developed a similar type of tension infiltrometer with slight modification in its design. They also automated the infiltrometer for precise infiltration measurement by using pressure transducers. Later, other workers (Ankeny, 1992; Jarvis and Messing, 1995) installed data loggers with the infiltrometer to reduce physical labour and also to achieve very accurate measurements.

Tension infiltrometers have already been used for determining *in situ* hydraulic properties of soil (Perroux and White, 1988; Ankeny et al., 1988,1991, 1990a, 1990b; Elrick and Reynolds, 1992; Warrick, 1992; Logsdon and Jaynes, 1993; Hussen and Warrick, 1993a, 1993b; Felton, 1992; White and Sully, 1987; Smettem and Clothier, 1989; Bohne et al., 1993; Nachabe, 1995). Earlier tension infiltrometers were designed to measure the increase in air pressure during flood or border irrigation (Dixon, 1975). More recently, tension infiltrometers have frequently been used to investigate the effects of weather conditions (White and Perroux, 1989; Messing and Jarvis, 1993), soil biotic activity (Clothier et al., 1985) and tillage practices (Ankeny et al., 1990a; Sauer et al., 1990) on near-saturated hydraulic properties at the soil surface. White et al. (1992) have recently presented a comprehensive review of the use of tension infiltrometers to determine soil hydraulic properties in the field.

### Modified Tension Infiltrometer (UNCEL type)

Tension infiltrometer of CSIRO type (Perroux and White, 1988) has been modified. A modified tension infiltrometers (designated as "UNCEL" University of New Castle Environmental Laboratory) type has been constructed (Fig. 1). A new detachable bubble tower has been designed and its performance tested against the CSIRO type. During modification the criterion for selection of different parts and their dimensions have been followed as mentioned by Perroux and White (1988). A different cloth has been selected to use increased suction range up to 35 cm of water pressure.

### Design, Construction and Assembly

The basic design of the tension infiltrometer is a double Mariotte-bottle arrangement, which is connected to a disc that contains an annular pore for water discharge. The infiltrometer is fabricated from a clear perspex cast-acrylic (RS Instrument Components Ltd., UK) material. The transparent perspex material helps observation of the total operation and any leakage can easily be observed. The outer diameter of the circular disc is 210 mm, the effective diameter through which water drains is 200 mm. At the center of the disc a hole is drilled and fitted with a small tube (5 mm height) having outer and inner diameters of 10 mm and 6 mm respectively. Around the water outlet point, a circular ring of 6 cm high is erected which acts as holder for the water reservoir. Just beside this another circular ring of the same height attached with the upper surface of disc to hold the bubble tube. Both the holders have an inner diameter exactly same as the outer diameter of the water reservoir and the bubble tower. The height and inner diameter of the reservoir are 1000 mm and 44 mm respectively. The bubble tower is 200-300 mm high and has an inner diameter of 29 mm. At the top of the bubble tower, an air-exit tube is fitted and connected to the air-entry point located on the disc. The inner diameter of the air exit and entry tubes are 6 mm, i.e. the same as the diameter of the water entry point. On the surface of the disc a small elongated area is drilled and a glass tube having a diameter of 3 mm is inserted. This tube conveys the controlled air pressure from the bubble tower to the bottom of the disc inside the water reservoir (Fig. 1).

The most conspicuous feature of the infiltrometer is its new bubble tower. The new feature of the bubble tower is that it has multiple air-entry tubes. This allows the quick application of precise tension on the upper vadose zone surface. It contains five tension (air-entry) tubes to generate tensions at 10, 20, 30, 40, 50, 100, and 150 mm of water potential respectively. Each air-entry tube is closed with a rubber valve.

For the supply membrane, a special non-absorbing nylon material, mono-filament filter (Cadish Precision Meshes Ltd., UK) was selected. The mesh of the supply membrane is 40 µm with an air-entry value of 37.5 cm of $H_2O$. Thickness of the supply membrane is 0.15 mm which has permeability of $9.4 \times 10^{-6}$ m/sec. Since the nylon membrane has a bubbling point 37.5 cm, therefore maximum tension should be up to 35 cm or less. In practice, tension settings of 3 to 15 cm have proven convenient across a variety of soils and soil conditions (Ankeny et al. 1992; Smettem and Clothier, 1989; Jarvis et al. 1987). White and Perroux (1989) opined that it is in this range (i.e., 15 cm) that biological and environmental factors, and soil management practices often have their greatest influences. Considering these facts and the problem of air-entry, in the modified bubble tower the maximum tension has been limited to 15 cm. The main feature of the newly designed infiltrometer is that its components are detachable. All the tension tubes and air exit tubes are externally fitted. This facilitates the accuracy of infiltration measurements during the time of changing the tension.

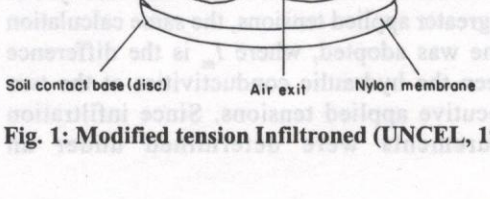

**Fig. 1: Modified tension Infiltroned (UNCEL, 1995).**

## Advantages

The modified infiltrometer has several practical advantages. In particular, its detachable components make it convenient and easy for transportation in the field site. Weight of tension infiltrometer is approximately 1.4 kg. For field transportation whole parts can be carried within a 1 m long and 30 cm wide box. If any components are damaged or any leak is observed, it can be repaired or can be changed with a spare on the spot. The use of cast-acrylic perspex instead of poly-carbonate has reduced its construction cost significantly. This infiltrometer is considerably cheaper ($80), and more versatile, than any other infiltrometer reported so far. Other advantages are: accurate and very precise application of tension, easy filling of reservoir, lower water requirement (1.5 liter), and minimal disturbance of the soil surface.

## Tension Infiltration Theory

The purpose of this section is to briefly review the theories and methods that have been related to the measurement of tension infiltrometer. On the basis of the existing theories, a calculation scheme has been adopted and an interpretation technique is presented to infer the water-flux behavior of the upper vadose zone. When infiltration reached a steady-state condition, Wooding's (1968) equation is appropriate:

$$Q = \pi r^2 \, \Delta K \left(1 + \frac{4\lambda_c}{\pi r}\right) \qquad (1)$$

where Q is the flow rate from the disc infiltrometer, r is the radius of the disc, $\lambda_c$ is the macroscopic capillary length, and $\Delta K = K(\psi_o)-K(\psi_n)$, where $K(\psi_o)$ is hydraulic conductivity at the soil surface and $K(\psi_n)$ is the hydraulic conductivity at the antecedent soil water potential, respectively. An approach based only on Wooding's solution (Eq. 1) is possible when steady-state flow rates are known for two or more disc radii (Scotter et al., 1982; Smettem and Clothier, 1989). For steady flow, equation 1 is solved for two unknowns ($\Delta K$ and $\lambda_c$), with $Q_1$ and $Q_2$ corresponding to disc radii $r_1$ and $r_2$ when:

$$\lambda_c = \frac{\pi}{4}\left[\frac{Q_1 - Q_2}{\frac{Q_2}{r_1} - \frac{Q_1}{r_2}}\right] \tag{2}$$

Substituting the value of $\lambda_c$ in to equation (1) hydraulic conductivity can be determined. The same principle can be applied for a single-disc radius with multiple tensions (Ankeny et al., 1991; Reynolds and Elrick, 1991; Hussen and Warrick, 1993b) by using the Gardner (1958) relationship:

$$K(\psi) = K_{fs}\,\exp(\alpha\psi) \tag{3}$$

which is assumed with ψ the matric potential expressed as length, $K_{fs}$ is saturated hydraulic conductivity, and a constant equivalent to $\lambda_c^{-1}$.

## Adopted Scheme of Calculations for UNCEL Type Infiltrometer

Infiltration from the circular disc source of a tension infiltrometer is usually calculated by noting the change of the water volume of the reservoir. For longer time, when infiltration reaches a steady-state condition, the volume change is divided by the area of the disc to get the steady-state infiltration rate as:

$$Q_t = \frac{Q}{A} = \frac{Q}{\pi r^2} \tag{4}$$

where $Q_t$ is the observed steady state infiltration rate from the tension infiltrometer, $A$ is the area of disc and $r$ is radius of the disc. For three dimensional, unconfined steady flow from a circular disc source of radius $r$, Wooding (1968) proposed the following approximate expression for infiltration rate q:

$$q = K(\psi)\left[1 + \frac{4}{\pi r\alpha}\right] \tag{5}$$

where $q$ is the measured infiltration rate. $K(\psi)$ is the unsaturated hydraulic conductivity at supplied water potential $\psi_o$, α is inversely proportional to the "macroscopic capillary length" (Eq. 1) (White and Sully, 1987). Gardner's (1958) equation was adopted to determine both the saturated and unsaturated hydraulic conductivity with Woodings (Eq. 5) as:

$$q = K_{fs}\,\exp(\alpha\psi)\left[1 + \frac{4}{\pi r\alpha}\right] \tag{6}$$

Equation (3) contains two unknowns viz, $K_{fs}$ and α. So it is necessary to have at least two equations of the form of equation (6) to solve for the two unknowns. If infiltration measurements are made at two or more potentials, a non-linear least-square regression of equation (6) can be used to determine the two unknowns (Logsdon and Jaynes, 1993). Unsaturated hydraulic conductivity is determined by substituting values of $K_{fs}$ and into equation (3). The effective macroporosity by combining the capillary and Poiseuille's equations as (Wilson and Luxmore, 1988):

$$q = \frac{8\mu I_n}{g\rho r_p^{2}} \tag{7}$$

where θ is total effective macroporosity, μ is the viscosity of water, and $I_m$ is the hydraulic conductivity of macropores. The parameter $I_m$ is determined as the difference between the hydraulic conductivity at the smallest imposed tension and the hydraulic conductivity at the tension at which macropores empty. Minimum pore radius of respective applied tension was used in equation (7) to determine the total effective macroporosity. For other greater applied tensions, the same calculation scheme was adopted, where $I_m$ is the difference between the hydraulic conductivities at the two consecutive applied tensions. Since infiltration measurements were determined under an approximately steady sate condition, a unit hydraulic gradient is assumed.

The hydraulic conductivity as a function of pressure is simply:

$$Q_t(\psi) = K(\psi) \qquad (8)$$

From adapted equations 3 and 6 we can determine both saturated and unsaturated hydraulic conductivities of upper vadose zone to be examined. So, in equation 8, the unsaturated hydraulic conductivity at each imposed tension was used as $I_m$. Since saturated hydraulic conductivity implies the flux of water at saturation, so this flux is used as "0" tension. If once the tension infiltrometer has been able to generate and measure the macropore flow, we may use equation (7) to get the total effective porosity as mentioned earlier. Later, results obtained from equation (7) can be used to calculate the number of hydrologically effective pores "N" per unit area for each size class (i.e., size ranges corresponding to tensions, 0-1, 1-3, 3-5, 5-10 and 10-15 cm) as follows (Wilson and Luxmore, 1988):

$$N = q/\pi r_p^2 \qquad (9)$$

From the proposed applied tension we can get two different porosity classes, namely "macroporosity" related to the tension 1 and 3 cm of $H_2O$ and "mesoporosity" related to the greater than 3 cm of $H_2O$ tension, respectively (Luxmore, 1981).

## Experiments in Uncompacted and Compacted Upper Vadose Zone

Unsaturated infiltration experiments were conducted with UNCEL type infiltrometer on reconstructed soil-cores at two bulk densities. Soil with the lower bulk density is designated "uncompacted upper vadose zone", while that with the higher bulk density is designated "compacted lower vadose zone". In each soil column five infiltration measurements were conducted. In between infiltration measurements, the soil was allowed to drain and to evaporate one week to achieve similar initial moisture content. There were no statistically significant differences in any measured parameters between the two replicate columns used in each case. Therefore, the results are presented as mean of these two columns.

## Soils and Soil Column

The soils of two soil columns are of Enborne series (Palmer, 1982) and clay loam (Soil Survey Staff, 1975) in texture. "A" horizon of the Enborne series was collected from the experimental farm of the University of Newcastle upon Tyne, U.K., in May 1995. The soils were transported to the soil-drying laboratory and air dried for about a week. Later soils were ground by a mechanical grinder and passed through a 2 mm mesh. Two soil columns were used, made of PVC (polyvinyl chloride) having a diameter of 50 cm and 150 cm in height. The lower 10 cm was filled with fine gravel, and the upper 140 cm with experimental soil A constant water table having a depth of 100 cm was mentioned in both soil-columns with a mariotte water-supply bottle. The bottom of each column was fitted with a tap to allow drainage of water.

## Upper Vadose Zone Preparation

Among two soil columns, one was used for uncompacted experiment (UESC) and other is for compacted experiment (CESC). Up to 90 cm, each soil-column was filled with Enborne soils. Rest 50 cm were filled with five layers of soils, each 10 cm thick. From the upper surface of each layer, soils were collected to determine bulk density and initial moisture contents. For uncompacted treatment no external pressure was applied to the soil surface. In the compacted treatment, each layer of soil was compacted by applying pressure from the top. A spherical compactor (20 cm of diameter and 4 kg weight) was used to compact the soil. Before adding the next layer of soil, the surface of the previous layer was scratched and loosened down to 4-5 mm deep. This was done so the soil layers could join together without separation. The average bulk density up to the 50 cm depth for uncompacted treatment was $1.086\pm0.36$ gm cm$^{-3}$. For compacted treatment, the average bulk density up to the same depth was $2.132\pm0.026$ gm cm$^{-3}$. Initial moisture content of the experimental depth was almost identical ($0.024\pm0.011$ m$^{-3}$).

## RESULTS AND DISCUSSION

The observed steady-state infiltration rates were determined from the equation 4. On the basis of the observed steady-state infiltration, the saturated hydraulic conductivity was determined using Wooding's (Eq. 6). Unsaturated hydraulic conductivity was determined from equation.3. Number of pores, percent of soil volume, percent of soil flux were determined form equations 7, 8 and 9 respectively.

### Steady State Infiltration

The observed and calculated steady-state infiltration rates of upper vadose are presented in Table 1. Compacted experiment show a reduction in observed infiltration at 1, 3, and 5 cm of applied tension in comparison to the uncompacted experiment. For others two higher tensions (10 and 15 cm) infiltration rates are almost identical. Calculated and observed steady-state infiltration rates of upper vadose zone are very close, except at 10 and 15 cm tensions (Fig. 2).

### Hydraulic Conductivity

The saturated hydraulic conductivities of upper vadose zones are lower after compaction. A decrease in unsaturated hydraulic conductivity is also observed in compacted vadose zone. The response of hydraulic conductivity to changes in tension was analyzed by examining the linear relation of log conductivity on tension (Fig. 3). Such semi-log transformations were suggested by Wind (1955) and are effective in linearizing treatment effects ( linear regression correlation are $r^2 = 0.99$ and $r^2 = 0.99$), reflected the use of Gardner's equation (Eq. 3). The relationship between observed, calculated steady-state infiltration and unsaturated hydraulic conductivity to respective tensions is shown Fig. 3.

**Table 1: Statistical analysis of hydraulic properties of upper vadose zone in uncompacted and compacted experiment.**

| Properties | Experiment: Uncompacted (mean±s.d.) (C.V.%) | Experiment: Compacted (mean±s.d.) (C.V.%) | Differences between experiment |
|---|---|---|---|
| Satatuarated hydraulic Conductivity $K_{fs}$ (cm $h^{-1}$) | 0.5263±0.0654 (12) | 0.2752±0.0488 (18 ) | *** |
| Observed steady state infiltration rate (cm $h^{-1}$) | | | |
| - 1 | 0.7133±0.0592 (12 ) | 0.3726±0.0427 (21) | *** |
| - 3 | 0.4984±0.0339 (7 ) | 0.2372±0.0347 (15) | *** |
| - 5 | 0.3919±0.0457 (12) | 0.1451±0.0378 (26) | ** |
| - 10 | 0.0881±0.0207 (23) | 0.0896±0.0191 (21) | NS |
| - 15 | 0.0355±0.0060 (18) | 0.0326±0.0061 (19) | NS |
| Calculated steady state infiltration rate (cm $h^{-1}$) | | | |
| - 1 | 0.7255±0.0550 (8) | 0.3653±0.0397 (11) | *** |
| - 3 | 0.5004±0.0398 (8) | 0.2432±0.0315 (13) | *** |
| - 5 | 0.3458±0.0365 (11) | 0.1629±0.0310 (19) | *** |
| - 10 | 0.1383±0.0273 (20) | 0.0608±0.0237 (39) | *** |
| - 15 | 0.0558±0.0162 (29) | 0.0238±0.0131 (55) | ** |
| Unsaturated conductivity (cm $h^{-1}$) | | | |
| - 1 | 0.4294±0.0431 (10) | 0.2233±0.0321 (14 ) | *** |
| - 3 | 0.2956±0.0226 (8 ) | 0.1478±0.0155 (10 ) | *** |
| - 5 | 0.2038±0.0162 (8 ) | 0.0985±0.0127 (13 ) | *** |
| - 10 | 0.0812±0.0128 (16) | 0.0366±0.0111 (30 ) | *** |
| - 15 | 0.0326±0.0082 (25) | 0.0140±0.0067 (49 ) | ** |

NS,significant at P<10%, (N.S) significant at 5≤P10%, * significant at 1≤P<5%, ** significant at 0. 1≤P<1%, ***significant at P<0.1% confidence level.

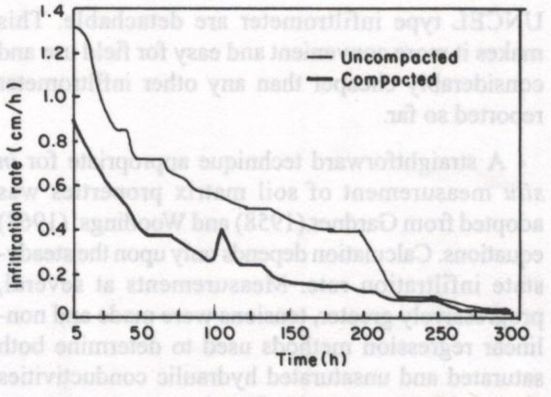

**Fig. 2: Infiltration rate at different tensions in uncompacted and compacted experiments of upper vadose zone.**

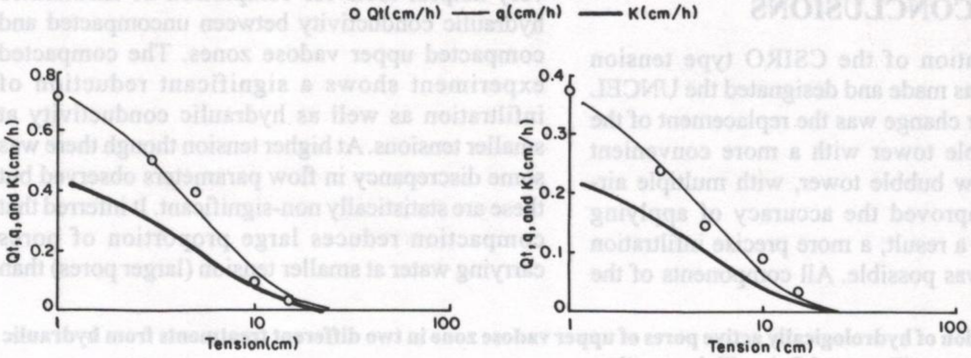

**Fig. 3: Relationship between steady state infiltration rates and unsaturated hydrolic conductivity of upper vadose zone.**

## Water Flux and Different Pore Size Classes

Pore sizes are inversely related with tension (Rowell, 1994). Unsaturated hydraulic conductivities of soil increase non-linearly with increasing diameter of pore (Fig. 4). However, the rate of increase decreases with increasing diameter of pore. The unsaturated hydraulic conductivity of uncompacted upper vadose zone is higher than that of compacted upper vadose zone (Fig. 5) and the differences increase with increasing diameter of pore.

## Hydrologicaly Effective Pore Classes and Their Contribution to Flow

The number and size of the hydrologically active pores has been analysed (Watson and Luxmore, 1986, Wilson and Luxmore, 1988). Table 2 shows that number of such pores decreased due to compaction. Uncompacted experiment shows approximately 18%, 25%, 17%, 23% and 9% of the saturated flux occurred passed pores having diameter of 0.3-.01 cm, 0.1-0.06 cm, 0.06-0.03 cm, and 0.03-0.02 cm respectively and 8% pass through <0.02 cm pores. Nearly 43% of saturated flux passed through the macropores (>1 mm) and the rest (57%) through remaining soil matrix/micropores. Though compaction of upper vadose zone reduces the number of pores and the saturated hydraulic conductivity (Table 2b) the proportion of the saturated flux passing through the different pore sizes (Table 2a) is very similar to that of the uncompacted soil (Table 2b).

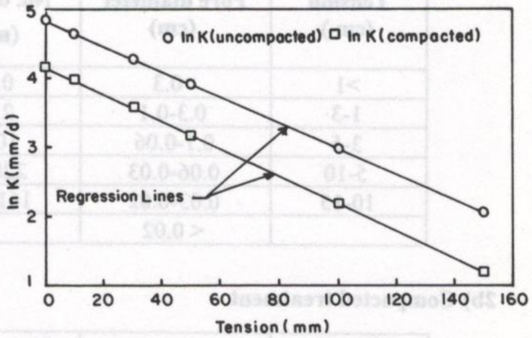

**Fig. 4: Relationship between hydraulic conductivities and applied tensions in uncompacted and compacted experiments of upper vadose zone. The solid lines are linear regressions having the equation in K= -0.018V + 4.82 ($r^2$ = 0.99) and in K = -09.019V + 4.173 ($r^2$ = 0.99) for the uncompacted and compacted soil respectively.**

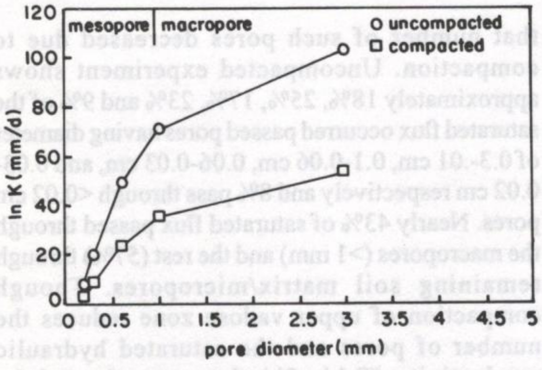

**Fig. 5: Relationship between pore diameters and unsaturated hydraulic conductivities of uncompacted and compacted experiments of upper vadose zone.**

## CONCLUSIONS

A modification of the CSIRO type tension infiltrometer was made and designated the UNCEL type. The major change was the replacement of the prototype bubble tower with a more convenient design. The new bubble tower, with multiple air-entry tubes improved the accuracy of applying tension and, as a result, a more precise infiltration measurement was possible. All components of the UNCEL type infiltrometer are detachable. This makes it more convenient and easy for field use and considerably cheaper than any other infiltrometer reported so far.

A straightforward technique appropriate for *in situ* measurement of soil matrix properties was adopted from Gardner (1958) and Woodings' (1968) equations. Calculation depends only upon the steady-state infiltration rate. Measurements at several, progressively greater, tensions were made and non-linear regression methods used to determine both saturated and unsaturated hydraulic conductivities along with unsaturated infiltration rates.

The UNCEL type tension infiltrometer proved very helpful tools for comparison of unsaturated hydraulic conductivity between uncompacted and compacted upper vadose zones. The compacted experiment shows a significant reduction of infiltration as well as hydraulic conductivity at smaller tensions. At higher tension though there was some discrepancy in flow parameters observed but these are statistically non-significant. It inferred that compaction reduces large proportion of pores carrying water at smaller tension (larger pores) than

**Table 2: Estimation of hydrologically active pores of upper vadose zone in two different treatments from hydraulic conductivity data, capillary and Poiseuille's equation.**

**2a) Uncompacted experiment**

| Tension (cm) | Pore diameter (cm) | No. of pore ($m^{-2}$) | Percent of soil volume | Percent of saturated flux |
|---|---|---|---|---|
| >1 | >0.3 | 0.02 | 1.27E-05 | 18 |
| 1-3 | 0.3-0.1 | 2.02 | 0.00015 | 25 |
| 3-5 | 0.1-0.06 | 10.71 | 0.00031 | 17 |
| 5-10 | 0.06-0.03 | 228.75 | 0.00161 | 23 |
| 10-15 | 0.03-0.02 | 1617.13 | 0.0051 | 9 |
|  | < 0.02 |  |  | 8 |

**2b) Compacted treatment**

| Tension (cm) | Pore diameter (cm) | No. of pore ($m^{-2}$) | Percent of soil volume | Percent of saturated flux |
|---|---|---|---|---|
| >1 | >0.3 | 0.01 | 6.84E-06 | 19 |
| 1-3 | 0.3-0.1 | 1.14 | 8.96E-05 | 28 |
| 3-5 | 0.1-0.06 | 5.75 | 0.00016 | 18 |
| 5-10 | 0.06-0.03 | 115.50 | 0.00082 | 22 |
| 10-15 | 0.03-0.02 | 798.17 | 0.00251 | 8 |
|  | < 0.02 |  |  | 5 |

of pores carrying water greater tension (smaller pores). In other words we may say that compaction destroy more lager pores (macropores) than the smaller pores (meso- or micropores). Ankeny et al. (1990a and 1990b) used tension infiltrometry to observe how tillage and wheel traffic compaction alters pore structure and hydraulic properties of agricultural soils. Their observation is consistent with the findings of the present study.

The UNCEL tension infiltrometer is able to demarcate the pore sizes those actively conducting water during unsaturated infiltration. The newly designed bubble tower is capable of differentiating between flow regimes governed by the macro-micro porosity of upper vadose zone. In the present study, however, the number of macropores is negligible, contributing a total porosity of approximately 8.36 x $10^{-5}$ $m^{-3}$ and consisting only 2-30 pores $m^{-2}$, but they carry about 44-46% of the total flux in each experiment. Watson and Luxmore (1986) reported that for field soil, macropores account for 73% of the total flow. Since the present experiments were conducted on homogenous reconstructed soil, a lower proportion of macropore flow was not unexpected.

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