A Critical Review of Single Ring Cylinder Infiltrometers with Lateral Flow Compensation

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Introduction

Predicting infiltration rates is among the most important aspects in planning, designing, and managing groundwater recharge systems, flood water retention basins and other infiltration systems. Knowledge of soil infiltration rates determines the capacity of the soil to receive water and ultimately how much land surface will be required to meet the infiltration demand of the engineered system. The saturated hydraulic conductivity (*K*) of the wetted zone is theoretically equal to the final large scale steady-state infiltration rate assuming uniform soil properties and the absence of influencing factors such as soil clogging, biological activity, and entrapped air (Bouwer, 1966).

Infiltration rates have been commonly determined with cylinder infiltrometers. (Bouwer 1986). A cylinder is filled with water and a constant water depth is maintained while measuring the flow of water into the cylinder. The test is continued until steady state infiltration rates are reached or approached, which may take several hours for finer, less permeable soils.

The principal source of error in single-ring cylinder infiltrometer measurements is divergence of water flow in the soil due to lateral unsaturated flow (Bouwer, 1960; Bouwer 1986). This divergence causes the measured infiltration rate inside the cylinder to be significantly higher than rates measured at the field scale where edge or divergence effects are small. The relative amount of lateral flow also increases with finer textured soils due to the presence of greater capillary suction associated with these soils. Lateral flow will also increase in response to the presence of lower permeable layers within the zone of influence of the cylinder.

The double-ring infiltrometer was introduced in an effort to eliminate the effects of divergence on measured infiltration (Bouwer 1986; ASTM, 2009); It is hypothesized that outer ring infiltration shields the inner ring from lateral divergence and therefore inner ring infiltration rates accurately measure the large scale infiltration. However, researchers have shown that inner ring measurements can also be highly influenced by lateral gradients and divergence flow, producing measurement error commensurate with a single-ring cylinder infiltrometer (Bouwer, 1960). Consequently, Bouwer et al. (1999) proposed a lateral divergence correction method for the single ring infiltrometer test. This paper compares the results of several single-ring, double-ring and larger scale infiltration test results in an effort to evaluate the validity of the Bouwer et al. (1999) correction method.

Single-ring Infiltrometer Method with Lateral Correction

The Bouwer et. al (1999) divergence correction method provides a rapid and simple procedure to correct for lateral convergence and it can also be used to converts short-term infiltration rates to a field (effective) saturated hydraulic conductivity (*K*). The method is a modified version of the air-entry permeameter (Bouwer, 1966) using a lateral wetting correction factor and an estimated air-entry value to estimate the hydraulic gradient.
The procedure consists of conducting a conventional single ring infiltration test. At the conclusion of the test, a shovel is used to partially dig out the wetted soil to determine the wetting depth and distance (*x*) of lateral divergence. Because flow in the wetted zone is mostly downward, vertical flow can be assumed in the entire wetted zone, and the corresponding downward flow rate, i_w, in the wetted zone is corrected for lateral divergence as the ratio of wetted area to cylinder area, using the equations shown in Figure 1. In essence, the Bouwer et al., correction method quantitatively determines the depth of the wetting front and extent of lateral divergence to solve *K*.

Parameter Sensitivity Analysis

The cylinder infiltrometer calculated field *K* values are affected primarily by the infiltration rate (i_n), and the lateral wetting distance (x), both of which are measured values. The degree of effect of lateral divergence on subsurface flow will be predominately controlled by the water entry value, duration of wetting and presence or absence of a less permeable layer within the wetted depth (L). A sensitivity analysis of h_{we} , L and estimated fillable porosity (*n*) was performed to determine the extent of potential errors in the calculated field *K* for a range of these parameter values. Changing h_{we} from -10 to -30 cm results in a 17 % decrease in effective *K.* Changing the wetting depth by a factor of 2 (82 to 41 cm) decreases effective *K* by 27%. This indicates that errors in estimated values for h_{we} and *L* may have up to a 30 % error which is less than the spatial variability observed in most field observations. Various authors (e.g., Nielsen et al., 1973) have shown that field *K* measurements of similar soils may vary by an order of magnitude or more and are typically log-normally distributed.

Double Ring and Corrected Single Ring Infiltrometer Comparison

Single-ring cylinder infiltrometer (50cm diameter) measurements using the Bouwer et al., 1999 correction method and double-ring cylinder infiltrometer measurements (60 and 30 cm diameter) were conducted side by side in seven different flood retention basins located in Maricopa County, Arizona. A total of seven sets of measurements were made in sandy soils and two sets in a silty loam. The measured infiltration rates from the double-ring infiltrometer (both inner and outer rings), the uncorrected measured infiltration rates from the single-ring cylinder infiltrometer tests and the lateral divergence corrected single ring infiltration rate are presented in Table 1. A geometric mean is chosen to evaluate the average rates due to typically log-normally distributed *K* of similar soils (Nielson et al., 1973).

For the sand soil, the average infiltration rate for the outer ring was 16 percent higher than the inner ring rate. However, two out of the seven inner ring rates were higher than the outer ring rates. The mean infiltration rate of the uncorrected single ring tests was the same as the mean outer double ring rate, providing reasonable evidence that the ring measurements sampled the same soil types. After correcting for lateral divergence, the estimated mean single ring infiltration rate is 4.6 times less than the inner ring measured infiltration rate and the effective *K* is 6 times lower than the measured inner ring rate. For the finer silty loam soil, the corrected single ring *K* was 2.7 times less than the measured inner ring infiltration rate.

Table 1. Comparison of Double Ring and Corrected Single Ring Infiltrometer Results.

Location and Material Type	**Double Ring**		**Single Ring**		
	Infiltration Rate	**Infiltration Rate**	**Uncorrected Infiltration**	**Corrected Infiltration**	**Effective *K***
	Outer Ring (m/day)	**Inner Ring** (m/day)	**Single Ring** (m/day)	**Single Ring** (m/day)	**Single Ring** (m/day)
#1 (sand)	15.8	10.9	11.2	2.3	1.8
# 2 (sand)	18.7	15.3	21.6	4.5	3.7
# 3 (sand)	21.6	28.2	17.3	3.0	2.5
# 4 (sand)	21.6	15.7	27.4	4.8	3.7
# 5 (sand)	24.3	21.6	19.4	3.4	2.7
# 6 (sand)	23.0	15.2	34.6	6.1	5.1
# 7 (sand_	28.8	31.6	31.7	5.9	3.2
Geometric Mean Sand	**21.7**	**18.6**	**21.9**	**4.1**	**3.1**
#1 (silty loam)	not meassred	0.069	0.060	0.035	0.013
#2 (silty loam)	not meassred	0.020	0.033	0.028	0.014
Geometric Mean Silty loam	not meassred	**0.037**	**0.044**	**0.031**	**0.013**

Large Scale and Corrected Single Ring Infiltrometer Comparison

Single-ring cylinder infiltrometers measurements were made at three different groundwater recharge sites using the Bouwer et al., (1999) correction method and compared to the infiltration rates measured in larger scale basins at these sites.

Small-scale Basins (3 m by 3 m for 16 hours)

Ten single-ring cylinder infiltrometer tests were conducted within and outside four 3 m x 3 m infiltration basins. Two test basins were placed in silty sand and two test basins in coarse sand. One single-ring cylinder infiltrometer test was performed inside each of the infiltration test basins before they were flooded. Additional single-ring cylinder infiltrometer tests were performed in backhoe test pits near the test basins. Test basins were then filled to a depth of 45 cm. and allowed to drain to a depth of approximately 15 cm before being refilled. Steady state was reached after 4 to 6 hours and the tests were run for 12 to 16 hours. After the small-scale basin test was completed, the extent of lateral wetting from the test basin was determined by backhoe excavation and was used to correct for the lateral wetting from the large basins.

The corrected *K* values from the single-ring cylinder infiltrometer tests in the coarse sand soils ranged from 0.46 to 4.18 m/day, with a geometric mean of 1.49 m/day. The average corrected infiltration rate for the two coarse sand basins was 1.78 m/day which compares favorably to the 1.49 m/day measured with the single ring infiltrometers. The corrected *K* values measured with the single-ring infiltrometers in the silty sand ranged from 0.24 to 0.40 m/day (geometric mean of 0.30 m/day). These values were slightly lower than the average corrected small-scale basin infiltration rate of 0.51 m/day for the silty sand.

Large-scale Test Basin (2.2 hectares for 7 day infiltration cycles)

Four single-ring infiltrometer tests were conducted at the surface and two at 30 cm depth in a 2.2 hectare test basin. The surface and near surface soils consisted primarily of silty sands and clayey sands with finer soils located 30 to 90 cm in depth. The basin was then filled with secondary treated effluent seven days before the basin was allowed to partially drain. A second seven day infiltration cycle was performed after which the basin was allowed to completely drain. Inflow rates and water depths were recorded over the time of the two flood cycles to predict the effective *K*.

The daily infiltration rates from the flooded basin ranged from 6.7 to 13.1 cm/day and averaged 9.1 cm/day. The geometric mean effective *K* of the single ring infiltrometer tests was 7.3 cm/day which agrees well with the measured basin infiltration rate.

Long Term Basin Test (0.4 hectares for 5 months)

A 0.4 ha test recharge basin was operated continuously for 5 months. The test basin soils consisted of fine sandy loams and loamy fine sands. Two cylinder infiltrometer tests were run in the basin prior to operation. Corrected single ring effective *K* results were 32 and 16 cm/day with a geometric mean of 21 cm/day. Initial infiltration rate in the basin was 51 cm/day and decreased to 15 cm/day after five months of continuous flooding. The geometric mean infiltration rate for the test period was 24 cm/day which compares well with the corrected single infiltrometer results.

CONCLUSIONS

The Bouwer et. al (1999) divergence correction method greatly improves the accuracy of single-ring cylinder infiltrometer measurements by quantitatively measuring the wetting front and lateral divergence. The speed of the method allows large numbers of measurements to assess wide spatial variability in soils. As shown with the field test comparisons herein with larger scale basins, estimates of infiltration rates determined with the single-ring infiltrometer method agreed favorably with measured infiltration rates. The ASTM D3385-03 double ring infiltrometer test method performs poorly in comparison because the test method does not account for lateral wetting, in addition to being much slower and more labor intensive. Moreover, the authors have performed more than 300 corrected single ring infiltrometer tests in the last 15 years and data to date indicates the procedure yields results that are a good estimate of large scale infiltration rates.

The method does have some limitations. Measurement errors greatly increase in soils with low permeability and because of this it is recommended that the procedure be limited to soils with permeability greater than 0.005 m/day. Lower permeable soils require longer infiltration times and other methods (i.e. air entry permeameters) are more suited to these soil types. Other sources of error include estimating the water entry and fillable porosity values, however, these errors are minor compared to typical changes in hydraulic conductivity due to spatial variability in soils. Larger potential sources of error are in the determination of the lateral wetting distance and wetting depth. Accurate measurements of these parameters are easily determined in dry or relatively dry soils, but if the soil is wet, the accuracy of the results is greatly decreased if the exact distance of lateral wetting and depth cannot be determined. The use of a portable water content probe (i.e. TDR or FDR) is useful in these cases to determine the lateral wetting and wetting front depths.

References

American Society for Testing and Materials. 2009 Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometers. D3385-03 ASTM, Philadelphia, PA.

Bouwer, H., 1960. ‘‘A study of final infiltration rates from ring infiltrometers and irrigation furrows with a resistance network analog.’’ *Proc., Comm. VI, Soil Tech., Trans., 7th Int. Congr. of Soil Sci.*, 448-456

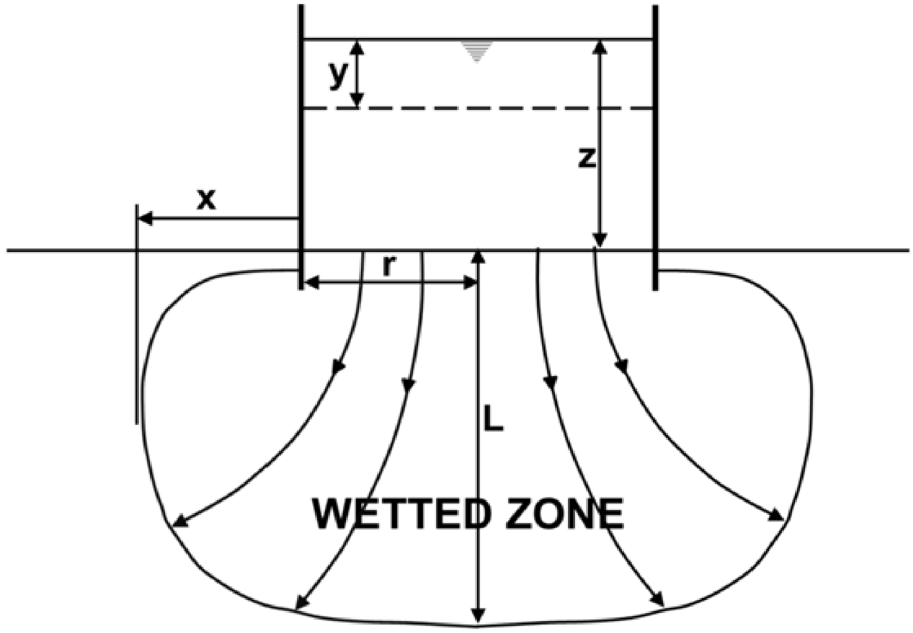
Bouwer, H., 1966. “Rapid Measurement of Air-Entry Value and Hydraulic Conductivity of Soil as Significant Parameters in Flow Systems Analysis.” Water Resour. Res. 2, 729-738.

Bouwer, H., 1986. ‘‘Intake Rate: Cylinder Infiltrometer.’’ Methods of Soil Analysis, Part 1, Physical and Mineralogical Methods, Agronomy Monograph No. 9, 2nd Ed., Am. Soc. Agron., Soil Sci. Soc. Am., Mad¬ison, Wis., 825–855.

Bouwer, H., 1994. ‘‘Estimating the ability of vadose zones to transmit liquids.’’ Handbook of vadose zone characterization and monitoring**,** L. G. Wilson, L. G. Everett, and S. J. Cullen, eds., Lewis, Boca Raton, Fla.,

Bouwer, H., Back, J.T., Oliver, J.M., 1999. Predicting Infiltration and Ground Water Mounds for Artificial Recharge, J Hydro Eng, ASCE, (4) pp. 350-357

Nielsen, D.R., J.W. Biggar, and K.T. Erh. 1973. Spatial Variability of Field-Measured Soil-Water Properties. Hilgardia, Vol 42, pp. 215-219.



$$i_w = \frac{i_n r^2}{(r+x)^2} \qquad K = i_w \frac{L}{z + L - h_e}$$

i_n : measured infiltration rate
L: wetting depth
x: lateral extent of wetting
r: cylinder radius
h_e : water entry pressure
z: ponded water depth
K: hydraulic conductivity

Figure 1. Geometry Symbols and equation for Single-Ring Infiltrometer