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Analysis of Double-Ring Infiltration Techniques and Development of a Simple Automatic Water Delivery System

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Abstract

Double-ring infiltrometers are routinely used by turfgrass specialists, soil scientists, and other professionals to measure the infiltration rate of field sites. Measurement of infiltration rate is important in proper golf course design development and other scenarios that require estimates of runoff. This study compared several commonly performed double-ring infiltration methods as follows: 30- (inner) and 60-cm (outer) diameter rings with a constant water depth (head), 15- (inner) and 30-cm (outer) diameter rings with a constant head, and 15- (inner) and 30-cm (outer) diameter rings with a falling inner head. In addition, a Mariotte siphon device was fabricated to maintain a constant inner head for the 15-cm diameter rings. The 15- and 30-cm rings with the constant head resulted in significantly higher infiltration rates compared to 30- and 60-cm diameter rings with a constant head and 15- and 30-cm rings with a falling head. This was due to variation in the 30- and 60-cm test inner ring water level that had to be maintained manually and because of the non-constant water level in the 15- and 30-cm falling head test. Thus, we concluded that the constant head 15- and 30-cm double-ring test was adequate to represent the infiltration rate in the sandy soils tested. The Mariotte siphon device made it easy for one person to conduct a test while maintaining a constant inner head under infiltration rates ranging from 22 to 225 mm/h.

Introduction

Infiltration is the process by which water arriving at the soil surface enters the soil. This process affects surface runoff, soil erosion, and groundwater recharge. Being able to measure the surface infiltration rate is necessary in many disciplines. The double-ring infiltrometer is often used for measuring infiltration rates, and has been described by Bouwer (5) and by ASTM (3). These references contain standard guidelines for conducting double-ring infiltration tests; however, in practice a wide variety of testing methodologies are used.

Ring infiltrometers consist of a single metal cylinder that is driven partially into the soil. The ring is filled with water, and the rate at which the water moves into the soil is measured. This rate becomes constant when the saturated infiltration rate for the particular soil has been reached. The size of the cylinder in these devices is one source of error. A 15-cm diameter ring produces measurement errors of approximately 30%, while a 50-cm diameter ring produces measurements errors of approximately 20% compared to the infiltration rate that would be measured with a ring of an infinite diameter (10). It has been suggested that a diameter of at least 100 cm should be used for accurate results (5). However, cylinders of this size become very difficult to use in practice on light soils, because large volumes of water are required to conduct tests on sandy soils with high infiltration rates.

Single-ring infiltrometers overestimate vertical infiltration rates (5,10). This has been attributed to the fact that the flow of water beneath the cylinder is not purely vertical, and diverges laterally. This lateral divergence is due to capillary forces within the soil, and layers of reduced hydraulic conductivity below the cylinder. A number of techniques for overcoming this error have been developed (such as a correction procedure that uses an empirical equation) for 15-cm diameter rings (10). Double-ring infiltrometers minimize the error associated with the single-ring method because the water level in the outer ring forces vertical infiltration of water in the inner ring. Another possible source of error occurs when driving the ring into the ground, as there can be a poor connection between the ring wall and the soil. This poor connection can cause a leakage of water along the ring wall and an overestimation of the infiltration rate. Placing a larger concentric ring around the inner ring and keeping this outer ring filled with water so that the water levels in both rings are approximately constant can reduce this leakage (5).

The double-ring infiltrometer test is a well recognized and documented technique for directly measuring soil infiltration rates (3,5). Bouwer (5) describes the double-ring infiltrometer as often being constructed from thin-walled steel pipe with the inner and outer cylinder diameters being 20 and 30 cm, respectively; however, other diameters may be used.

There are two operational techniques used with the double-ring infiltrometer for measuring the flow of water into the ground. In the constant head test, the water level in the inner ring is maintained at a fixed level and the volume of water used to maintain this level is measured. In the falling head test, the time that the water level takes to decrease in the inner ring is measured. In both constant and falling head tests, the water level in the outer ring is maintained at a constant level to prevent leakage between rings and to force vertical infiltration from the inner ring. Numerical modeling has shown that falling head and constant head methods give very similar results for fine textured soils, but the falling head test underestimates infiltration rates for coarse textured soils (12).

The ASTM standard (3) describes a procedure for measuring the soil infiltration rate with a double-ring infiltrometer for soil with a hydraulic conductivity between 1×10^{-2} and 1×10^{-6} cm/s (360 mm/h to 0.036 mm/h). The ASTM standard specifies inner and outer diameters of 30- and 60-cm, respectively. There are also some minor differences in the method that is suggested by the standard compared to that described by Bouwer (5).

The primary objective of this research was to compare falling head and constant head double-ring tests with 15- and 30-cm rings and a constant head test with 30- and 60-cm diameter rings. A secondary objective was to develop a simple device to automatically maintain a constant water level in 15-cm diameter inner ring.

Infiltration Measurement Methods

An area at the Irrigation Park on the University of Florida campus in Gainesville, Florida was used to conduct the double-ring infiltrometer tests. The area was approximately 5 m by 15 m and was covered by a permeable black plastic sheeting to prevent weed growth. This cover was removed for testing purposes. The soil was an Arredondo fine sand (11), which had been tilled and allowed to settle for several months. Soil textural analysis indicated 92% sand, 4.5% silt, and 3.1% clay (6). The three types of tests that were evaluated were the ASTM standard 30-cm (inner) and 60-cm (outer) double-ring infiltrometer under a manually maintained inner ring constant head (A), 15-cm (inner) and 30-cm (outer) infiltration rings under an inner ring constant head with a Mariotte siphon (B) and 15-cm (inner) and 30-cm (outer) infiltration rings under a falling head (C). In all three types of tests, the outer ring was maintained manually at a constant head. Maintaining a constant head in the outer ring was not as critical as maintaining constant head in the inner ring to measuring infiltration rates since the purpose of this head is to reduce the leakage of water between rings. The 15- and 30-cm infiltration ring size is typically used in turfgrass systems such as golf courses for infiltration measurements. In many cases, the falling head test is preferred since less water and time are required to complete a test.

A total of eight tests in different locations within the experimental site were conducted using method (A), which followed the procedure set out by the ASTM standard. Nine infiltration tests each were conducted using methods (B) and (C). One fewer of the method (A) tests was conducted because substantially more water was required for this test compared to the smaller rings and not enough water was available to run the final test with the large rings.

Fig. 1. Photograph of (A) 30-cm diameter (inner) and 60-cm diameter (outer) double-ring infiltrometer (B) 15-cm diameter (inner) and 30-cm diameter (outer) double-ring infiltrometer, and (C) Mariotte siphon developed to maintain a constant inner head in the infiltration rings.

Both the small (15 and 30 cm) and large (30 and 60 cm) sets of double rings were manufactured out of 2.5-mm thick aluminum (Fig. 1). These rings were driven into the ground approximately 15 cm for (A) and 5 cm for (B) and (C) using an 18-kg hammer and a 10-×-10-×-75-cm block of wood. A Mariotte siphon was manufactured from a 10.2-cm inner diameter Plexiglass pipe cut to a length of 120 cm (Fig. 1). This resulted in approximately 12.5 liters of water storage, sufficient to keep a constant head in a 15-cm diameter inner ring for more than 4 h assuming an infiltration rate of 150 mm/h and for 1 h assuming an infiltration rate of 700 mm/h. The 30-cm diameter inner ring used in the ASTM Standard test would require approximately 50 liters of water to keep a constant head for 1 h assuming an infiltration rate of 700 mm/h. Two 130-mm PVC end caps were used to seal both ends of the Plexiglass pipe and a wooden base was built to support the siphon. A barbed pipe fitting was tapped into the bottom PVC end-cap and a 20-mm diameter hole was drilled into the top end-cap. A 1.5-m long, 15-mm diameter PVC pipe was then placed within the siphon (Fig. 2) and a rubber stopper was used to create an airtight seal between the end-cap and pipe. Adjusting the level of the tube allowed the pressure at the outlet of the siphon to be either increased or decreased. The height of the bottom of the pipe above the siphon outlet was equal to the water level in the inner ring of the infiltrometer. A graduated tape was placed on the outside of the siphon to allow the water level in the siphon to be recorded at a regular time interval. The water level in the outer ring was maintained manually by adjusting a flow valve on a water container (38 liters) that was used to supply water to the outer ring of the double-ring infiltrometer. Alternatively, another Mariotte siphon could be used to maintain a constant water level in the outer ring; however, the water level could be maintained manually with sufficient precision to minimize lateral flow or leakage from the inner ring. Cumulative infiltration and time were recorded, with each test generally lasting 40 to 90 minutes for the constant head test and approximately 20 to 30 minutes for the falling head test. The bulk density and volumetric moisture content of the soil were measured adjacent to each test site before each infiltration test was conducted using standard laboratory procedures (1,2,4,8). The infiltration rate was found by regressing the recorded cumulative infiltration and time data using Sigma Plot (SPSS, Chicago, IL). The GLM procedure in SAS (SAS Institute, Inc., Cary, NC) was used to produce an Analysis of Variance (ANOVA) to test for statistical differences between infiltration rates and Duncan's Multiple Range Test was used for means separation.

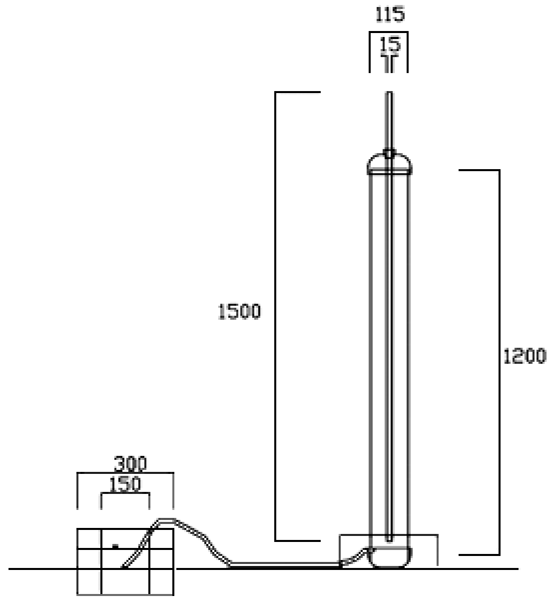

Fig. 2. Mariotte siphon developed for infiltration rate testing with 15- and 30-cm inner and outer rings of a double-ring testing apparatus. Dimensions in millimeters.

Evaluating Measured Infiltration Rates

Table 1 shows the results of the measured infiltration rates from the three different testing methods. Measured infiltration rates on the sandy soil ranged from 22 to 225 mm/h and averaged 143 mm/h over all tests (Table 1). These rates are representative of moderately compacted fine sandy soils such as has been documented on pasture sites (9). Testing methods (A) and (C) resulted in a significantly lower mean infiltration rate (119 and 128 mm/h, respectively) compared to method (B) at 179 mm/h (P = 0.0492) (Table 2). This difference was expected for the falling head test (C) since the depth of water in the inner ring, one of the components of total head which causes infiltration, decreases during the test. This result is similar to results reported by Wu et al. (12). However, it is unknown why the large rings at constant head resulted in lower infiltration rates. One possibility is that the large volume of water required to maintain water level in the inner ring was manually controlled; therefore, contributing to an increase in the incidence of human error since the larger the volume of water that is manually added the more difficult it is to be precise in the application of that water. Test (B) had the lowest CV at 24% compared to tests (A) and (C) at 39% and 37%, respectively. It was observed that one test with (A) and one with (B) resulted in infiltration rate outliers. Using boxplots, these values were between one and a half and three box-lengths from the 25th percentile (7).

Table 1. Statistical analysis of infiltration rates (K) from three types of infiltration tests[z].

Test A ASTM standard with 30- and 60-cm dia. rings[x]		**Test B** Constant head with 15- and 30-cm dia. rings[x]		**Test C** Falling head with 15- and 30-cm dia. rings[x]	
Test no.	K (mm/h)	Test no.	K (mm/h)	Test no.	K (mm/h)
1	120	1	79	1	161
2	147	2	225	2	56
3	110	3	171	3	128
4	164	4	196	4	100
5	N/A[y]	5	209	5	186
6	86	6	190	6	80
7	152	7	201	7	197
8	152	8	151	8	119
9	22	9	192	9	125
Mean	119	Mean	179	Mean	128
Std dev	47	Std dev	43	Std dev	47
CV	39%	CV	24%	CV	37%

[z] Note, the overall mean infiltration rate was 143 mm/h, with a standard deviation of 52 mm/h and a CV of 36%.

[y] Test 5 for (A) not conducted.

[x] Note that 15- and 30-cm rings refer to inner and outer ring diameters, respectively and 30- and 60-cm ring diameters refer to inner and outer ring diameters, respectively.

Table 2. Results of an ANOVA for measured infiltration rates using different testing methodologies (tmt = infiltration test and rep = replication).

Source	**Type III sum of squares**	**DF**	**Mean square**	**F**	**Pr > F**
tmt	161.8	2	80.9	3.71	0.0492
rep	151.8	8	19.0	0.87	0.5624
error	327.5	15	21.8		

Although the outliers observed in (A) and (B) are commonly found in infiltration testing (9), they were removed and the analysis was repeated. Test (B) still had a mean infiltration rate (192 mm/h) higher than tests (A) and (C) (133 and 128 mm/h, respectively). Test (B) infiltration rate remained significantly higher (P = 0.0180) than (A) and (C). By removing the outliers in the two tests, the overall CV was reduced to 19%.

Volumetric moisture was not significantly different across testing locations with all data or with the outliers removed (P = 0.0789 and P = 0.1073, respectively). Soil bulk density was not significant across testing locations in the full data set (P = 0.0789) but was significant when the outliers were removed (P = 0.0278). Test (A) sites had a higher soil bulk density of 1.53 g/cm^3 in the upper 6 cm compared to test (C) at 1.47 g/cm^3. Bulk density at (A) was similar to test (B) at 1.50 g/cm^3. Although soil bulk density was higher on (A), there was not a correlation with infiltration rate over all tests (r = 0.1893) or with outliers removed (r = 0.1394). In addition, tests of covariance between soil moisture content and infiltration rate and between soil bulk density and infiltration rate indicated no covariance between infiltration rate and soil moisture or soil bulk density.

A typical 15- and 30-cm ring test required approximately 60 liters of water (inner and outer ring) and the constant head was easily maintained with the Mariotte siphon. As previously mentioned, the constant head in the large ring (30 and 60 cm) tests was maintained manually. This required a substantial amount of water to be manually added (approximately 115 liters), thus the actual head maintained varied.

Summary of Infiltration Studies

The use of smaller diameter inner and outer rings (15 and 30 cm, respectively) with a constant head provided results that were statistically higher than the ASTM standard test and the falling head test with small rings. Both the ASTM and the falling head tests resulted in higher CVs than the 15- and 30-cm ring constant head tests. This trend was more evident when outliers from the data set were removed. A higher soil bulk density on ASTM ring testing sites coupled with human error at maintaining the water level in the inner ring contributed to the high variability in this test. It was concluded that the test using a constant head with a double-ring infiltrometer of 15-cm inner diameter and 30-cm outer diameter would be suitable for infiltration research on the sandy soils generally found in North Central Florida. Previous measurements indicate these soils have similar infiltration rates to golf greens built to USGA specifications with mature turf (*data not shown*). This allows for infiltration tests to be conducted in areas where a methodology such as that specified by the ASTM would not be suitable due to insufficient spacing between obstacles or because the volume of water required to maintain a constant head in the larger diameter double-ring infiltrometers can not be transported to remote sites.

The set-up of the double-ring infiltrometer with the Mariotte siphon, as described in this paper is an efficient method of conducting a double-ring infiltrometer test. The Mariotte siphon automatically maintains a constant head in the inner ring, while the head in the outer ring is maintained manually (a second Mariotte siphon could be used for this). This testing procedure therefore only requires one person to maintain the head in the outer ring and record the change in water level in the siphon. The volume of water that is needed for this tests can also be managed by a single person compared to the large volume of water needed to conduct the ASTM standard test.

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