Evaluating the scale dependency of measured hydraulic conductivity using double-ring infiltrometers and numerical simulation

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Abstract
Saturated hydraulic conductivity measurements are important for understanding and modeling hydrological processes at the field scale. Few systematic studies have been conducted on how the size of double-ring infiltrometers affects the measured hydraulic conductivity. To determine this size effect, we measured saturated hydraulic conductivity at seven sites using four different sizes of double-ring infiltrometers. Inner ring diameters d_i were 20, 40, 80, and 120 cm. Detailed numerical investigations were also conducted to explain how the inner-ring size of a double-ring infiltrometer influences the measured hydraulic conductivity in a heterogeneous soil. Field and simulation results both demonstrated that the variability of measured hydraulic conductivity was greater for smaller inner rings (e.g. $d_i < 40$ cm), and it gradually decreases as the ring size increases. Our study indicates that where soil spatial variability is high, infiltrometers having a large inner ring (in general $d_i > 80$ cm) are essential for reliable measurement.

Key Words
Soil, saturated hydraulic conductivity, measured scale, double-ring infiltrometer, field experiments, numerical simulation

Introduction
Studies investigating the size dependency of ring infiltrometer measurements have mainly focused on lateral flow, and little attention has been devoted to size dependency caused by soil heterogeneity. Hydraulic conductivity measured in a heterogeneous soil is strongly linked to the representativeness of the measured volume. This representativeness involves both the representative elementary volume (REV), and the correlation scale of the hydraulic conductivity (Ciollaro and Romano, 1995). The objectives of this study were (i) to evaluate the effect of measurement size on the soil hydraulic conductivity, and (ii) to find the smallest diameter double-ring infiltrometer needed to cover a representative area for reliable soil hydraulic conductivity measurements in the semi-arid region of China.

Methods
Philip (1957) showed that cumulative infiltration I under water-ponded conditions is approximated at time t by:

$$I = S\,t^{0.5} + \mathrm{A}\,t \qquad (1)$$

where I is cumulative infiltration (L), S is sorptivity(L/T$^{0.5}$), and A is a constant (L/T). As time progresses, the first term becomes negligible and the importance of A, which represents the main part of the gravitational influence, increases (Koorevaar, *et al*., 1983). The A term can be taken as the saturated hydraulic conductivity of the wetted zone (K_w) after a long period of infiltration (Bouwer, 1986). This equation was applied to the data collected in the present study. By fitting Eq. (1) to the cumulative infiltration data, we obtained the saturated hydraulic conductivity K_w of the wetted zone for each infiltration test.

Field experiments
The field experiment was conducted in a long-term tillage plot within the Minqin oasis in the lower reaches of the Shiyang River (38°54′N, 103°03′E) in Gansu province, northwest China. Seven sites within the 100 × 100 m experimental plot were randomly selected, and the experimental sites are about 30 ~ 40 m away from each other. At each site, one measurement was taken with each of the four double-ring infiltrometers (see Figures 1-3), each in close proximity to the others.

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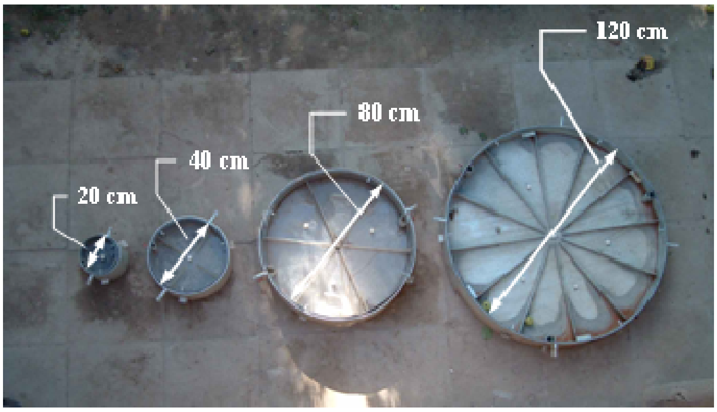

Figure 1. Photograph of the four sets of double-ring infiltrometers of different diameters (only inner-rings with nested-rings are shown here, the diameters of corresponding outer-rings, from left to right, are 70, 70, 100, and 140 cm, respectively).

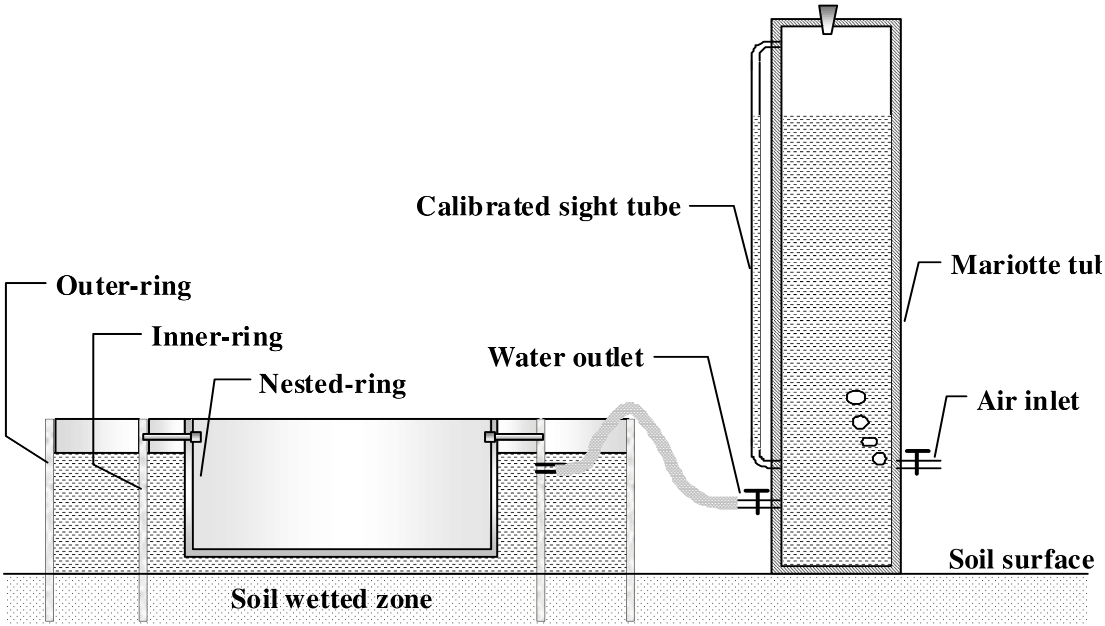

Figure 2. Cross-section sketch of the double-ring infiltrometer. (The nested ring, a cylinder with a base that was nested and fixed in the inner-ring by four pins, was held several centimeters above the soil surface, so it did not affect the infiltration process. The nested-ring had two functions: (i) it mainly reduces the upper free water area in the inner-ring, resulting in improved measurement accuracy; and (ii) it minimizes surface evaporative losses, especially for a long-term infiltration.)

Figure 3. Photograph of field experiment setup, double-ring infiltrometer (d_i = 40 cm, d_o = 70 cm).

Numerical Experiments
A series of numerical experiments was conducted to investigate how the inner-ring size of a double-ring infiltrometer influences the accuracy of the measured saturated hydraulic conductivity in heterogeneous soil. The two-dimensional model HYDRUS-2D (Šimůnek *et al*., 1999) was used to simulate infiltration under a double-ring infiltrometer.

Conclusions
It is generally known that soil saturated hydraulic conductivity (K_s), which is one of the parameters to describe the ability of water movement in soil, is similar for the same soil texture. When infiltrometers (Double-ring infiltrometer, Guelph infiltrometer, *et al*.) are used to determine saturated hydraulic conductivity, it is commonly assumed that the soil is homogeneous within the measured area. However, hydraulic conductivity can vary significantly within a short distance due to soil spatial variability and heterogeneity. This suggests that double-ring infiltrometers, widely used for determining the saturated hydraulic conductivity, may give scale-dependent results.

We have measured soil saturated hydraulic conductivity at seven sites using four different sizes of double-ring infiltrometers to identify the size dependency. In the study, the inner ring diameters, d_i, were 20, 40, 80, and 120 cm, and the soil textures at seven sites were similar. The results showed that the mean hydraulic conductivity does not change significantly over the full range of inner ring diameters, but the range and standard deviation of the measurements decrease appreciably with increasing d_i. As the ring size increases, the representativeness of the area covered by the infiltrometer also increases, so the measured hydraulic conductivity becomes more representative and stable.

How does the inner-ring size of a double-ring infiltrometer influence the measured hydraulic conductivity in various heterogeneous soil? It is necessary to investigate this size effect in more soil conditions. HYDRUS-2D was well performing in simulating the soil water infiltration process, detailed numerical investigations have been conducted for this purpose. In the study, six correlation lengths (L = 0 cm, 10 cm, 20 cm, 50 cm, 100 cm, and 200 cm) and six standard deviation values (SD = 0, 0.1, 0.25, 0.5, 0.75, and 1.0) of random field of log(K_s) were used for the various realizations of hydraulic conductivity fields. Ten realizations have been performed for each combination of (L, SD) treatment and infiltrometer diameter (10-, 20-, 40-, 80-, 120-, and 200-cm). Because only a single realization is needed when SD = 0, this gave a total of 1806 realizations, and it seems to conduct 10 replicates of field experiments for each infiltrometer at 31 different locations.

The study showed that the variability of measured hydraulic conductivity is greater for smaller inner rings (e.g. $d_i < 40$ cm), and it gradually decreases as the ring size increases. Where soil spatial variability is high, infiltrometers having a large inner ring (in general $d_i > 80$ cm) are essential for reliable measurement, large-diameter infiltrometers produce more stable values than small diameter ones, so they represent an efficient method for improving measurement representativeness.

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