IMPROVED APPARATUS FOR MEASURING HYDRAULIC CONDUCTIVITY AT LOW WATER CONTENT

JOHN R. NIMMO,* KATHERINE C. AKSTIN, AND KAREN A. MELLO

Abstract

A modification of the steady-state centrifuge method (SSCM) for unsaturated hydraulic conductivity (K) measurement improves the range and adjustability of this method. The modified apparatus allows mechanical adjustments to vary the measured K by a factor of 360. In addition, the use of different flow-regulating ceramic materials can give a total K range covering about six orders of magnitude. The increment of K adjustment is a factor of about 1.6. This makes it potentially useful for measuring targeted values of K or, through a trial and error procedure, of water content (θ). The range extension afforded by this modification has led to the lowest steady-state K measurement to date: 1.1×10^{-11} m/s at θ of 0.068 m^3 water/m^3 for a sandy soil of the Delhi series (mixed, thermic Typic Xeropsamment).

HYDROLOGIC PROBLEMS such as aquifer recharge determination and solute transport in the unsaturated zone require measurement of natural fluxes. If the flow is Darcian, these flux determinations require, besides driving force, a measurement of K at the in situ θ. The SSCM (Nimmo et al., 1987) has been developed primarily for the purpose of making K measurements of this type. For a fuller applicability to these problems, however, this method needs enhancement of its range, especially for low water contents, and also greater adjustability for measurements of the required values.

The basic SSCM uses the apparatus shown in Fig 1, consisting of water storage and flow control devices surrounding a soil column in a 1-L centrifuge bucket. This apparatus is exposed to centrifugal accelerations up to 2000 g to generate measurable flows even at low K values. Measurements of the change in weights of the various reservoirs indicate the flux (Q), and, dividing by the cross-sectional area of the sample, the flux density (q). When q becomes steady, Darcy's law applies, and K can be calculated by dividing q by the net driving force, a combination of centrifugal force and matric potential (ψ) gradient. Centrifugal force is easily determined but the ψ gradient generally must be measured or calculated using a numerical model based on Darcy's law. When the centrifugal force exceeds a certain threshold that depends on the soil hydraulic properties, the ψ gradient can become negligible. Nimmo et al. (1987) discussed various possibilities for this gradient and presented model calculations showing that it becomes negligible at relatively low speeds for a sandy medium and at higher speeds for a fine-textured medium. This negligible-gradient situation is favorable for at least two reasons. Once it has been verified, there is no need to determine the ψ gradient. It also permits the association of the sample-averaged θ and ψ values with the measured K.

The particular value of K measured in a given experiment is determined primarily by the constant-head or inflow reservoir, which controls the flux and spreads water over the soil surface. The overflow hole in this reservoir maintains a constant head of water above the ceramic plate, labeled B in Fig. 1, that serves as a flow resistance and spreading device. By selecting one of several overflow holes at different vertical positions, slight variations in head are possible. However, the maximum variation in q by this means is small because the range of possible heads is small. The use of different types of ceramic for Plate B, however, will change q in proportion to the saturated K of the ceramic, affording variations over discrete intervals covering a few orders of magnitude. Changes in centrifugal force also change q but, where ψ gradients are negligible, q remains proportional to the force, causing negligible change in K. These relations, discussed in further detail in Appendix B of Nimmo et

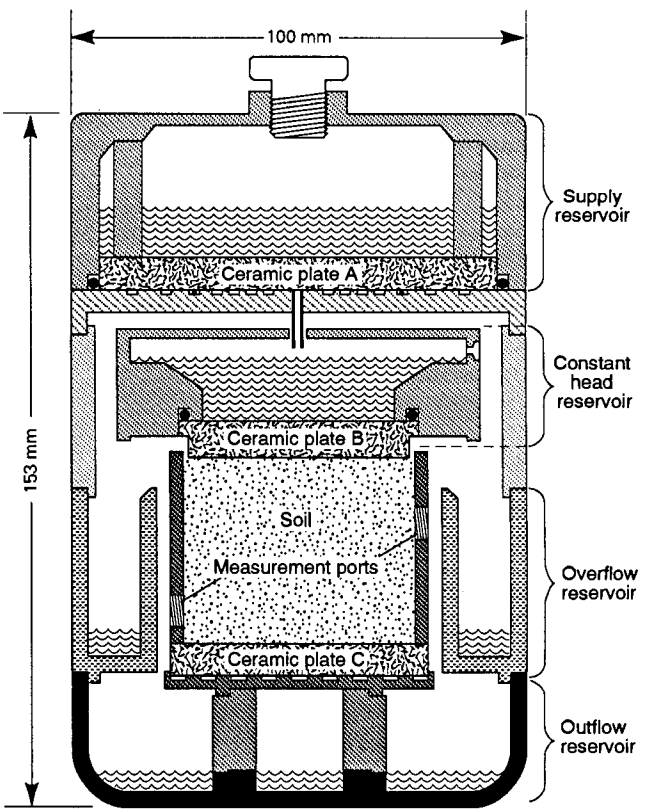

Fig. 1. Apparatus essentially equivalent to the original design of Nimmo et al. (1987) for measuring unsaturated hydraulic conductivity by the steady-state centrifuge method. The apparatus fits into a 1-L centrifuge bucket. Materials used for the nonporous components include stainless steel for the soil retainer, acrylic plastic for the supply reservoir, and aluminum for most other parts.

Water Resources Division, U.S. Geological Survey, MS-421, 345 Middlefield Road, Menlo Park, CA 94025. Received 8 July 1991. *Corresponding author.

Published in Soil Sci. Soc. Am. J. 56:1758–1761 (1992).

al. (1987), mean that the apparatus of Fig. 1 generally produces only one K–θ–ψ point for each type of ceramic available for use as Plate B.

We present a modification of SSCM that allows fine adjustment to obtain measurements at a previously designated value of K. It also extends the K and θ range of the method, especially to low θ values where there are no alternative methods for accurate K measurement.

Design and Testing

The key feature of the modified SSCM apparatus (Fig. 2) is a division of the flux-control and spreading functions of the inflow reservoir. The flux-controlling reservoir and applicator that replace the inflow reservoir are referred to as the *split-function reservoir system* because they perform flux control with one device and spreading of water over the soil surface with another.

The new flux-controlling reservoir permits adjustment of Q in three different ways:

1. An O-ring can be selected to match any one of seven concentric grooves under the ceramic plate labeled D, thereby changing the plate's effective area (A) by as much as a factor of 60. The flux is approximately proportional to A.
2. The overflow height can be adjusted as before, but across a much greater range (a factor of six) because the free-water surface can now be below the top of the ceramic plate. The flux is approximately proportional to the height (H) of the overflow level above the bottom surface of the ceramic plate. This proportionality is inexact because the centrifugal force increases linearly with distance from the center of rotation, making it greater in the lower than in the upper portion of the flux-controlling reservoir. An exact proportionality can be set up with a corrected quantity $\tilde{H}$, based on Eq. B3 of Nimmo et al. (1987), which differs from H by 6% or less. For a given ceramic disk, Q may be taken as proportional to the product $\tilde{H}A$, which can be adjusted through a factor of 360 by increments of about 1.6.
3. The device permits coarse adjustments by replacing Plate D with a ceramic plate of different conductivity. Ceramic materials we have tested cover an adjustment range of a factor of 2600. Together the three possible adjustments can permit variation of Q by as much as a factor of 10^6.

We tested the proportionality of Q and $\tilde{H}A$ by measuring Q for various combinations of $\tilde{H}$ and A. Figure 3 shows the results. There is some scatter, but the trend is consistent with the direct proportionality of Q and $\tilde{H}A$. There is a slight nonlinearity that suggests a tendency for the flux at low $\tilde{H}A$ to be somewhat greater than would be expected. This may result from the geometry of flow paths limited by an O-ring on only the lower side of the plate. The area A was computed from the O-ring diameter, but with one of the smaller O-rings in place, fringing effects may cause the effective flow-limiting area to be somewhat larger than the O-ring itself.

The applicator plate, labeled E in Fig. 2, does not receive water uniformly distributed over its surface. The design relies on spreading to take place on top of and within the ceramic plate so that water is uniformly applied to the soil. To verify the evenness of spreading, the split-function system was compared with the original reservoir system by alternating the two in 10 successive centrifuge runs of about 1-h duration, using a sandy soil as a test medium. To inhibit biological growth and to have reasonable electrolyte concentrations, the water used in this and other tests was a selenate solution (0.005 M $CaSO_4$ and 0.005 M $CaSeO_4$).

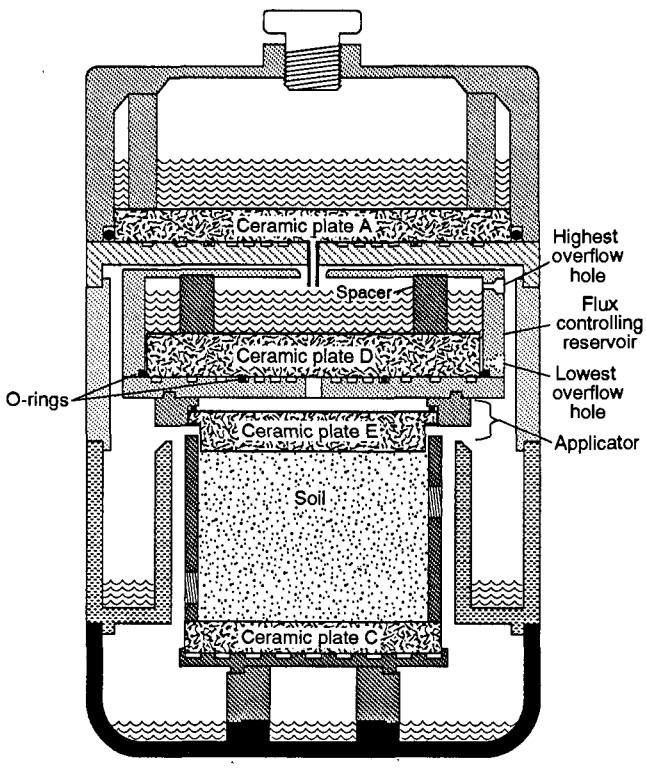

Fig. 2. Apparatus incorporating the split-function reservoir system. The applicator and flux- controlling reservoir replace the constant-head reservoir in Fig. 1.

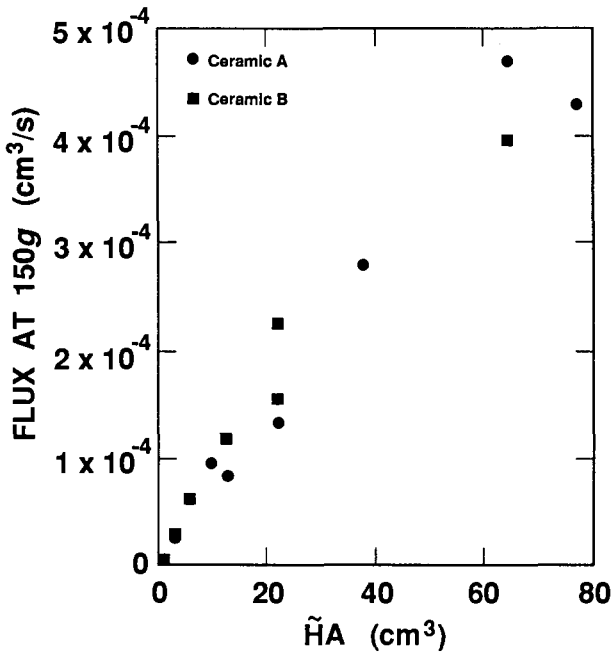

Fig. 3. Comparison of flux with the $\tilde{H}A$ factor, the product of the corrected height factor, $\tilde{H}$, and the area, A, of the ceramic through which water flows in the flux- controlling reservoir. Measurements were made with 500-kPa ceramic limiting the flow. Most of these measurements were made at an angular speed of 105.1 s. For graphing, results of the others were converted to their equivalent at 105.1 s by multiplying by the ratio of the centrifugal forces.

The flux through the split-function reservoir had been previously adjusted to match the flux through the original constant-head reservoir. Electrical resistance (R) was measured at the outside edge of the sample during each run using a two-electrode probe. A four-electrode probe would have given more consistent readings but, averaging the resistance across a larger portion of the sample, it would not have indicated whether the outside of the sample was drier than the center. Resistance was converted to θ by assuming θ to be inversely proportional to electrical conductivity (σ) and applying a previously measured $\theta(\sigma)$ relation for the same soil (Nimmo, 1990). If the split-function system spreads selenate solution as evenly as the original system, then R and θ would be the same for both.

The Q values obtained in the two types of devices were close enough for a valid test, as indicated by the means and standard deviations: 1.57 ± 0.59 cm^3 /s for the original system and 1.28 ± 0.71 cm^3 /s for the split-function system. Results for R were 155 ± 12 kΩ (original) and 163 ± 18 kΩ (split-function) and for θ were 0.100 ± 0.005 m^3/m^3 (original) and 0.096 ± 0.008 m^3/m^3 (split-function). Thus the R and θ measurements fell close enough together that there is no indication of uneven spreading. The variation in θ for this experiment was larger than expected from the typical experimental uncertainty of ±2% for steady-state centrifuge experiments (Nimmo et al., 1987; Nimmo and Akstin, 1988). Reasons for this include: (i) evaporation was significant because the electrical wires prevented use of the usual windscreen; (ii) each flux value was measured in a single centrifuge run instead of several runs; and (iii) the two-electrode resistance measurements were erratic.

The uniformity of spreading selenate solution over the soil by the applicator plate in the split-function reservoir was also tested visually. Indicating drierite (W.H. Hammond Co., Xenia, OH)[1], grain size 0.84 to 1.8 mm, was used in place of soil to observe any evidence of radial differences that might be caused by the spreading. The drierite changed color as water infiltrated. A clear polycarbonate retainer was substituted for the usual opaque soil retainer. A brief run of the apparatus at 1100 rpm (250 g) caused infiltration to a depth of 7 mm. Samples were excavated and transitions in color were observed to be uniform with depth to within 1.5 mm. No evidence of radial differences was found, confirming the uniform distribution of selenate solution by the applicator plate in the split-function reservoir system.

Results and Discussion

The split-function SSCM was used to measure unsaturated hydraulic properties of densely packed Oakley sand (now classified in the Delhi series). The samples used for this purpose were from the same batch and were prepared by the same procedure as the samples of Nimmo et al. (1987) and the D2F2C2 samples (porosity 0.333) of Nimmo and Akstin (1988). This medium is known to develop effectively uniform ψ profiles under steady-flow conditions at the 220 × g centrifugal acceleration used in this experiment. This permitted calculation of K by dividing the measured steady-state q by the known centrifugal force, and θ by dividing the total volume of water in the sample by the known sample volume. Values of q from three or more steady-state runs were averaged to obtain a K value. Matric potential was determined with a tensiometer brought into contact with the sample after a complete set of centrifuge runs.

Figure 4 compares K measurements from the split-function and standard reservoir systems. Table 1 gives water retention data based on ψ measurements after eight of the SSCM measurements. The experimental uncertainties indicated by error bars in Fig. 4 were determined by combining estimated measurement errors on each type of primary data. The experimental uncertainty of θ is somewhat greater for three of the five split-function values because a small amount of soil was lost from one sample between the time of the K measurements and the time of oven drying. The other uncertainties are essentially the same for the two systems. For K measurements with similar θ, results of the two reservoir systems agreed within experimental error, indicating that the split-function reservoir can parallel the accuracy of the original design. The split-function measurement of $K = 1.1 \times 10^{-11}$ m/s for $\theta = 0.068$ may be the lowest unsaturated K value measured by a steady-state technique.

The precise adjustability of the split-function SSCM makes measurements possible at targeted values of K.

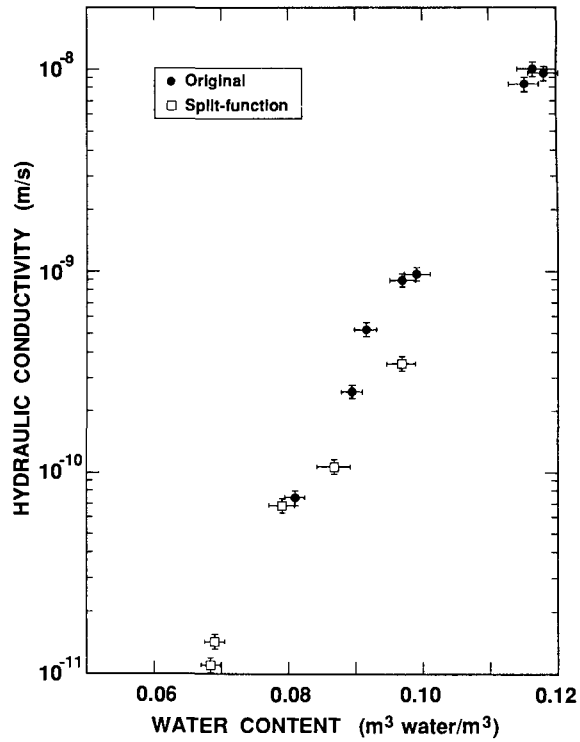

Fig. 4. Hydraulic conductivity vs. water content for Delhi soil, measured with original and split-function reservoir systems.

Table 1. Water retention of Oakley sand. Values of soil water pressure head (ψ) are tensiometer measurements and values of water content (θ) are sample averaged, both determined after steady-state centrifuge method (SSCM) measurements of hydraulic conductivity.

θ	ψ
m/m	kPa
0.115	−9.7
0.099	−13.0
0.097	−13.2
0.092	−14.7
0.090	−17.5
0.081	−27.0
0.069	−39.5
0.068	−42.0

[1] Use of this product name is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

For a given ceramic in the flux-controlling reservoir, a few measurements of the type plotted in Fig. 3 can establish the relation between Q and $\tilde{H}A$. Then Q can be predicted before a measurement, as can K if conditions are known to produce a negligible steady-state ψ gradient. If the ψ gradient is uncertain, a target K can be approached after two or more SSCM measurements establish the relation between Q and K. A sequence of trials of this sort can also permit targeting a specific θ, or ψ if hysteresis is negligible or can be corrected for. Where measurements at low K values are required, it is necessary to run the centrifuge at high speeds, in some cases higher than is now possible without breaking the ceramic applicator plate. Improvements can be made by the use of stronger materials, or by a redesign that independently supports the weight of the flux- controlling reservoir so that it does not rest on the applicator.

Tests have confirmed the adequacy of flux control and spreading of the split-function modification of the SSCM. Besides improving the precision of adjustability, the modification extends the range of the SSCM, permitting steady-state measurements at lower K and θ values than were possible before.

Acknowledgments

We are grateful to Judith Wright for suggesting the use of indicating drierite to test for uniformity of spreading.

References

Nimmo, J.R. 1990. Experimental testing of transient unsaturated flow theory at low water content in a centrifugal field. Water Resour. Res. 26:1951–1960.

Nimmo, J.R., and K.C. Akstin. 1988. Hydraulic conductivity of a sandy soil at low water content after compaction by various methods. Soil Sci. Soc. Am. J. 52:303–310.

Nimmo, J.R., J. Rubin, and D.P. Hammermeister. 1987. Unsaturated flow in a centrifugal field: Measurement of hydraulic conductivity and testing of Darcy's law. Water Resour. Res. 23:124–134.