### 3.6.1.1.b Steady-State Centrifuge

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**Introduction—Principles of the Methods.** Because of its adjustability and convenience for producing body forces much greater than gravity, centrifugal force is

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# Methods of Soil Analysis

## Part 4
## Physical Methods

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advantageous for hydraulic property measurement in several ways. It allows measurement of lower hydraulic conductivity (*K*) values, faster experiments, and higher accuracy than methods relying on gravitational and matric driving forces. Methods using centrifugally driven flow can directly measure the liquid flow properties that otherwise may not be distinguished from vapor effects or other phenomena.

Several centrifugal applications are static with respect to water flow, in particular for water retention and related measurements. Early techniques, starting with Briggs and McLane (1907), centered around the *moisture equivalent* concept, a single-number index of a soil's retention capacity that is no longer in use. In later work the water retention relation became the objective (Gardner, 1937; Russell & Richards, 1938; Hassler & Brunner, 1945; Alemi et al., 1976; Paningbaton, 1980). This type of method allows the water in an unsaturated sample to equilibrate with the centrifugal field, much as the hanging water column method (Section 3.3.2.2) allows it to equilibrate with a gravitational field. Especially in recent years, estimations of unsaturated hydraulic conductivity (*K*) have been made from such centrifuge-determined retention data by models such as those of Burdine (1953) and Mualem (1976) and using the fitted formula of van Genuchten (1980). These are not centrifugal measurements of *K*, however. This type of method is not discussed further here; this section treats the direct measurement of *K* with the possibility of simultaneous determination of water retention, but not the equilibrium (no inflow) method of measuring water retention alone.

Dynamic water movement in a centrifugal field is particularly useful to study porous media properties and behavior. This is sometimes done by physical modeling of dynamic situations such as soil mechanical and geotechnical modeling (Schofield, 1980). In these cases, the medium being centrifuged is considered as a physical model with both time and spatial dimensions scaled down by the great centrifugal force. It requires a centrifuge that is overwhelmingly larger than the sample, typically >1 m in radius, so that the centrifugal field in the model may closely approximate the uniformity of a gravitational field. If the sample is not considered a scale model but simply a medium subjected to a great force, it is possible to measure dynamic properties with a smaller, readily obtainable centrifuge. Methods based on this idea are the main subject of this section. Two types of implementations have been successfully used, one in which the means of controlling flow is internal to the centrifuge bucket, referred to here as *internal flow control* (IFC) (Nimmo et al., 1987), and the other in which the flow is controlled outside the centrifuge, called *unsaturated flow apparatus* (UFA) (Conca & Wright, 1998).

In some experiments, transient instead of steady flow (e.g., Alemi et al., 1976; Nimmo, 1990), and even unstable flow (Culligan et al., 1997; Griffioen et al., 1997), have been investigated. So far these have not led to generally used techniques for soil property measurements, though they provide significant insights into the nature of unsaturated flow.

The objectives of this section are to describe the steady-state centrifuge (SSC) apparatus and procedures, and to explain particular features of centrifugal force in the measurement of saturated and unsaturated hydraulic conductivity. The level of detail is not intended to suffice as a stand-alone instruction manual, but to allow the reader to understand each method and its corresponding apparatus, as well as the pros and cons.

*Basic Centrifugation.* A centrifuge bucket is constrained to move in a circular path so that it accelerates toward the center. An object within the bucket therefore feels driven toward the bottom of the bucket. Because this force on the object within the bucket is directed away from the center of rotation, it is called a *centrifugal* (meaning “away from center”) force. As basic physics textbooks (e.g., Resnick et al., 1992) explain, centrifugal force is a pseudo force, meaning that it exists only within the bucket, which is not a legitimate inertial reference frame because it is accelerated. But this only means that certain laws of mechanics do not apply; it does not mean that the object in the bucket feels no force or that the force is not centrifugal. The centrifugal force ($F_c$; N) increases linearly with distance from the center, and with the square of the speed of rotation. It can be expressed as

$$F_c = mr\omega^2 \qquad [3.6.1.1\text{–}2]$$

where $m$ is the mass of the object in the bucket, $r$ (m) is the distance from the center of rotation, and $\omega = 2\pi/t_c$ is the angular frequency (rad s$^{-1}$) with $t_c$ (s) being the time to complete one rotation. The factor $r\omega^2$ is the centrifugal acceleration, analogous to gravitational acceleration ($g$). Equation [3.6.1.1–2] and others derived from it, which retain the explicit $r$ dependence, permit the use of a sample whose height in the bucket is significant with respect to $r$, even though the force varies within the sample. When the object in the bucket is water in a porous medium, it is convenient to consider the centrifugal force per unit volume; that is,

$$F_{cv} = \rho_w r\omega^2 \qquad [3.6.1.1\text{–}3]$$

where $\rho_w$ (kg m$^{-3}$) is the density of water.

*Saturated Flow and $K_{sat}$ Measurement in a Centrifugal Field.* Especially for tight media, a technique using centrifugal force may be better than other techniques for measuring the saturated hydraulic conductivity ($K_{sat}$). Knowledge of $K_{sat}$ is not only important in itself, but also as an indicator of the maximum measurable unsaturated $K$ value. It allows operating speeds and flow rates for the unsaturated $K$ measurements to be chosen more appropriately.

The techniques available for measuring $K_{sat}$ in a centrifugal field are adaptations of familiar gravity-driven, constant- and falling-head methods (Section 3.4.2). Figure 3.6.1.1–1b and 3.6.1.1–1c illustrate two ways of implementing such a $K_{sat}$ measurement, with an internal (within the centrifuge bucket) or external (outside the whole centrifuge) constant or falling head (Nimmo & Mello, 1991). The internal or external option and the constant- or falling-head option permit four combinations, each with a somewhat different apparatus and formula. For the two internal head options (Fig. 3.6.1.1–1b), Nimmo and Mello (1991) derived the formula

$$K_{sat} = (2qL)/[\rho_w\omega^2(r_o^2 - r_{wa}^2)] \qquad [3.6.1.1\text{–}4]$$

for the constant-head case, and the formula

$$K_{sat} = \frac{\mathrm{a}L}{Ar_o\rho_w\omega^2(t - t_i)} \log\left[\frac{(r_o + r_{wa})(r_o - r_i)}{(r_o - r_{wa})(r_o + r_i)}\right] \qquad [3.6.1.1\text{–}5]$$

for the falling-head case, where $q$ is the flux density (m $s^{-1}$), $L$ is the sample length (m), $r_o$ (m) is the position at which the pressure potential $\psi = 0$ (Pa), as would be established by a free water surface, $r_{wa}$ (m) is the position of the inflow reservoir surface, $a$ ($m^2$) is the cross-sectional area of the reservoir, $A$ is the cross-sectional

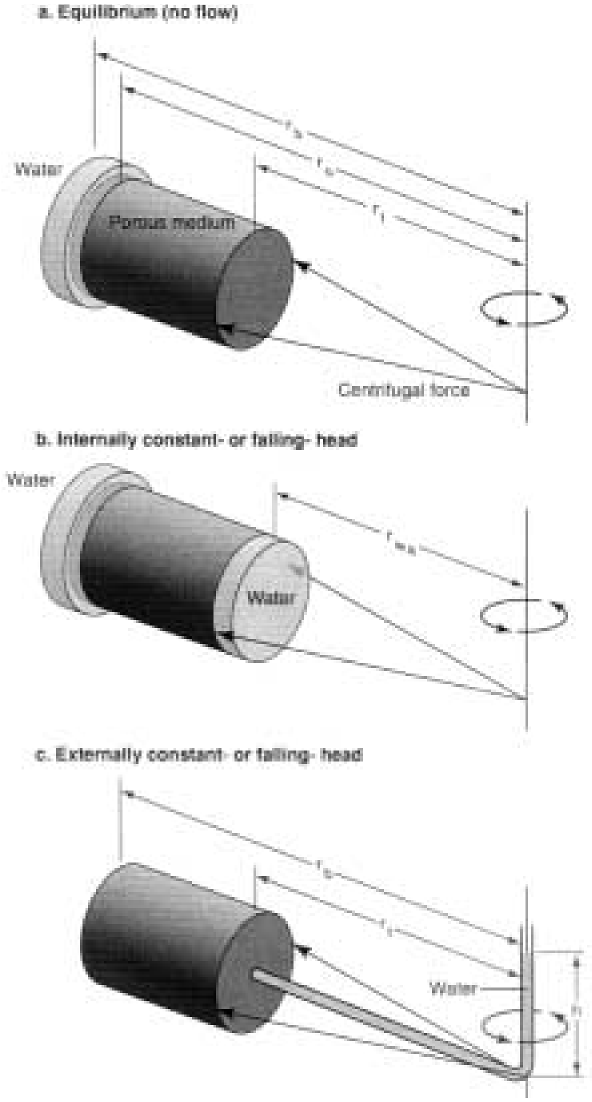

Fig. 3.6.1.1–1. Diagrammatic configurations for various means of hydraulic property measurements. (a) No-inflow condition with controlled outlet head to establish a static equilibrium distribution of water content and matric potential for water retention measurement. Note that $r_b$ is the distance from the center of rotation to the bottom of the porous medium, regardless of the bulk water level. (b) Internally applied constant or falling head condition as used to measure $K_{sat}$ in a standard-rotor centrifuge. Note that $r_{wa}$ is defined to supplement the dimensional definitions in (a). (c) Externally applied constant or falling head condition to measure $K_{sat}$ in a UFA-rotor centrifuge.

area of the sample, $t$ is time (s), and $r_i$ (m) is the position of the reservoir surface at time $t_i$ (s). In both of these formulas, $K_{\mathrm{sat}}$ takes on the seldom-used units of meters per second per pascals per meter, which can be converted to meters per second by multiplying by 9807 pascals per meter water (= $\rho_w g$). For the external-head options (Fig. 3.6.1.1–1c), combining these equations with the appropriate representations of gravity-driven flow gives

$$K_{\mathrm{sat}} = (qL)/(\rho_w g z_o + 0.5\omega^2 r_b^2) \qquad [3.6.1.1\text{–}6]$$

for the constant-head case, and

$$K_{\mathrm{sat}} = \frac{2aL}{A\rho_w g(t_f - t_i)} \ln\left[\frac{(gz_f + \omega^2 r_b^2)}{(gz_i + \omega^2 r_b^2)}\right] \qquad [3.6.1.1\text{–}7]$$

for the falling-head case, where $z$ (m) is the height of water above the plane in which the sample rotates, and $r_b$ (m) is the position of the bottom of the sample.

*Unsaturated Flow in a Centrifugal Field.* Steady-state conditions require a constant flow rate and a constant centrifugal force for a long enough time so that both the water content and the water flux within the sample are constant. When these conditions are satisfied, Darcy's Law relates $K$ to the volumetric water content ($\theta$) and the matric potential ($\psi$; Pa) for the established conditions. The air pressure is assumed to be atmospheric (zero) so the pressure potential and the matric potential can be equated (Koorevaar et al., 1983, p. 79). With a centrifugal instead of the gravitational force, Darcy's Law takes the form

$$q = -K[(\mathrm{d}\psi/\mathrm{d}r) - \rho_w\omega^2 r] \qquad [3.6.1.1\text{–}8]$$

Rearranging this equation yields

$$q/K = \rho_w\omega^2 r - (\mathrm{d}\psi/\mathrm{d}r) \qquad [3.6.1.1\text{–}9]$$

In the case of hydrostatic equilibrium (i.e., $q = 0$), Eq. [3.6.1.1–9] leads, upon integration, to a description of the pressure potential profile by

$$\psi(r) = [(\rho_w\omega^2 r)/2](r^2 - r_o^2) \qquad [3.6.1.1\text{–}10]$$

Figure 3.6.1.1–1a gives a diagrammatical illustration of the method. At hydrostatic equilibrium, the matric potential gradient is equal and opposite to the centrifugal driving force.

In the case of steady flow, the driving force is applied with a centrifuge rotation speed large enough to ensure that $\mathrm{d}\psi/\mathrm{d}r \ll \rho_w\omega^2 r$. Any matric potential gradient that develops in the sample during centrifugation is insignificant; the flow is essentially driven by the centrifugal force alone. The flow equation then simplifies to

$$q \approx K(\psi)\rho_w\omega^2 r \qquad [3.6.1.1\text{–}11]$$

The $\omega$ threshold value for which the $d\psi/dr$ gradient becomes negligible depends on the soil hydraulic properties. 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 centrifugally dominated situation is favorable for at least two reasons. First, once it has been verified, there is no need to determine the $\psi$ gradient. Second, it normally results in a fairly uniform water content throughout the sample, permitting the association of the sample average $\theta$ and $\psi$ values, determined from the sample weight and tensiometer readings, with the measured $K$. Repeat measurements with different $q$ values (and perhaps, e.g., different speed) give additional points needed to define the $K(\psi)$, $K(\theta)$, and $\theta(\psi)$ characteristics.

It is important to know the pressure boundary condition at the outflow face. This pressure can be controlled by applying a known head using a thick outflow membrane in a vessel that ensures the formation of a water table at a known position, as was done by Russell and Richards (1938), by Nimmo et al. (1987) during succeeding applications of the IFC apparatus, and by Nimmo (1990) during a transient flow experiment. A schematic diagram of the apparatus to be used is depicted in Fig. 3.6.1.1–2. A shallow-lipped metal plate in the outflow reservoir is grooved on its upper face to prevent sealing to the porous ceramic plate with which it is in contact. The relevant water table in Fig. 3.6.1.1–2 is not shown in detail, but would exist in the lowest millimeters of the ceramic plate, at the height of the outer lip on the metal plate. This method requires that the ceramic plate has a high enough $K$ value so that (i) flow occurs easily through it, and water does not accumulate in the sample and (ii) the pressure difference between the water table and the top of the ceramic plate is negligibly affected by flow through the membrane. A similar apparatus can be used to apply a positive $\psi$ in case a saturated $K$ measurement needs to be made (Nimmo & Mello, 1991). A more widely used alternative to the above setup is to allow water to exit the sample freely (except for the unavoidable impedance of the screen or filter that supports the bottom of the soil sample). The common assumption is that $\psi = 0$ at the outflow face, though this has not been experimentally demonstrated. Although this assumption is not true in an exact sense, it may be a reasonable approximation. Theoretically, water will accumulate at a slightly positive pressure until eventually water drops form and exit at the outflow face. Analogously to the concept of air-entry pressure, the system would have a slightly positive “water exit pressure”. On the other hand, the matric potential may be somewhat negative if instabilities enhance the drainage of some outlet-face pores, an effect that may be enhanced by the centrifugal force.

There are numerous effects that cause the net force field within the sample to deviate from uniformity, including:

1. The centrifugal force diverges radially from the axis of rotation, so that within the cylindrical sample it mostly is not parallel to the axis of the cylinder.
2. The centrifugal force varies substantially with $r$ (i.e., along the sample axis), although the explicit $r$ dependence in the equations accommodates for most aspects of this effect.

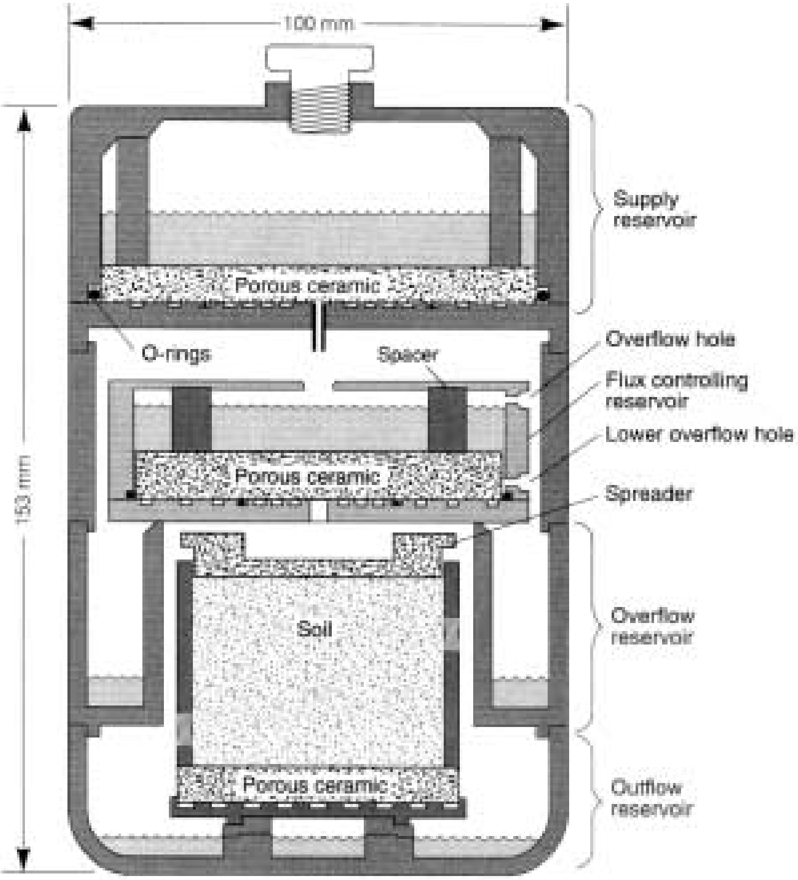

Fig. 3.6.1.1–2. Cross section, in the plane of rotation, of apparatus fitting in a 1-L centrifuge bucket for establishing and measuring steady-state flow through the soil (Nimmo et al., 1992, 1994). A twin apparatus is used in the bucket opposite the first one.

3. Strictly, gravity should be vectorially added to the centrifugal force. In the IFC system, the direction of the net force is not a problem as long as the bucket swings properly to align with the net force, in which case the magnitude only needs correction at low speeds. In the UFA, both the direction and magnitude of the net force may create a problem at low speeds.
4. Coriolis forces are usually negligible for conditions of unsaturated property measurement.
5. Forces arising from angular acceleration and deceleration may be significant at the start and end of a centrifuge run, but are likely to be negligible as long as the constant-speed portion of the run is much longer than the duration of acceleration and deceleration.

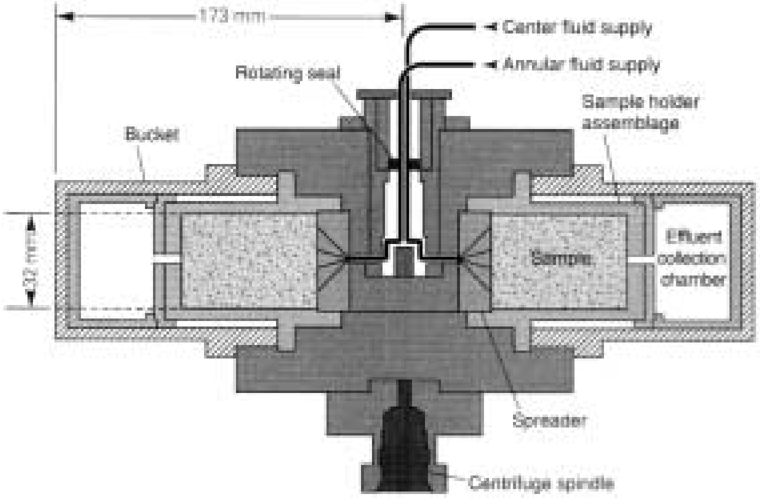

Fig. 3.6.1.1–3. Cross section, perpendicular to the plane of rotation, of the UFA rotor including two sample assemblies. The rotating seal and inflow tubes are not shown to scale to enhance the distinction of details. The filter paper and perforated plate at the outflow face of each sample are also omitted.

### Apparatus and Supplies.

*Steady-State Centrifuge-Internal Flow Control.* The basic SSC method with IFC uses the apparatus shown in Fig 3.6.1.1–2, consisting of water storage and flow control devices surrounding a soil column in a 1-L centrifuge bucket. This apparatus is subjected to centrifugal accelerations of up to 2000 $g$ to generate measurable flow even at low $K$ values. The reservoirs and porous plates control the water flow rate at the desired value, chosen to maintain a suitable state of unsaturated water content. Measurements of the change in mass of the various reservoirs indicate the volume flux ($Q$; m$^3$ s$^{-1}$). Dividing by the cross-sectional area of the sample gives $q$. When $q$ becomes steady, Darcy's Law applies, and $K$ can be calculated from Eq. [3.6.1.1–8] or [3.6.1.1–11]. A wide variety of centrifuge types and rotor types can be used to obtain these measurements by the SSC-IFC approach.

*Steady-State Centrifuge–Unsaturated Flow Apparatus.* The SSC–UFA method requires the use of a specific centrifuge and rotor, of which at least two models are commercially available. Figure 3.6.1.1–3 illustrates a UFA rotor designed for SSC measurements with certain Beckman centrifuges (Beckman Instruments, Fullerton, CA).[1] In addition to the specific equipment requirements, the dimensions of the rotor and sample retainers of the UFA system differ from the IFC system, and it also employs a different way of delivering water to the sample. The rotor pictured here uses sample retainers 4.9 cm long and 3.3 cm in diameter, resulting in a cross-sectional area of 8.55 cm$^2$ and a sample volume of 41.89 cm$^3$. Somewhat larger sample sizes are possible with an alternative larger version of the UFA rotor.

Rather than delivering water to each sample through use of an internal reservoir and ceramic plate applicator (internal flow control), water is supplied to each

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[1] The mention of brand names does not imply endorsement by the USGS.

sample through external pumps attached (via tubing) to the UFA rotor and the use of a rotating seal within the UFA rotor. External pumps control the rate at which water is delivered to each sample during centrifugation. Many types of pumps are available for use with the SSC-UFA rotor; for example, intravenous pumps from the medical industry are commonly used.

Water pumped into the rotor from an external water pump is dispersed over the sample through use of a specifically designed spreader. Testing of the evenness of dispersion has been performed by Conca and Wright (1998). Infused water, after passing through the sample, passes through a filter paper and perforated plate (both placed to prevent soil loss from the sample retainer) into an effluent collection chamber attached to the bottom of the sample retainer (Fig 3.6.1.1–3). The effluent chamber has calibration markings for measurement of outflow volume, useful for comparison to inflow when establishing steady-state flow. A centrifuge equipped with a strobe light can be used to observe the amount of effluent within the effluent collection chamber during centrifugation.

*Accessories and Supplies.* Additional equipment used with either the IFC or UFA version includes a balance accurate to 0.01 g or better, for weighing samples and effluent after centrifugation, and a timer for recording the elapsed time of centrifugation. A tensiometer (or other suitable device, for conditions outside the tensiometer range) is needed for measuring the matric potential associated with a given centrifuge run. This should be a touch type (nonintrusive) tensiometer (e.g., with a disk membrane that can be brought into temporary contact with the surface of the sample). Supplies commonly needed include de-aired water, antibacterial agents, filter papers of various sizes, O-rings, lubricants, and miscellaneous hand tools. Other sample preparation and handling equipment that may be necessary can be found in other sections of this book, and other publications addressing centrifuge techniques.

For use with the UFA apparatus, freshly de-aired water should be used for each centrifuge run, especially at high centrifuge speeds and low flow rates. Under these conditions, the infused water can be under high negative pressures. This can lead to dissolution of dissolved air and development of bubbles within the water delivery system, within the pumps, the tubing connecting the pumps to the rotor, or the rotor itself. Significant air bubbles can lead to inconsistent water delivery rates, pump failure and shutdown, and possible rotor face-seal damage.

Antibacterial agents previously used include calcium selenate or chlorinated water solutions. Calcium selenate solutions (0.005 $M$ $CaSO_4$ and 0.005 $M$ $CaSeO_4$) work well and work for extended periods. In particular, calcium selenate prevents bacterial clogging of ceramic plates used with the SSC-IFC apparatus. However, because calcium selenate tends to precipitate easily, this solution could damage the rotating face seal when used in the SSC-UFA rotor. Chlorinated water (sodium hypochlorite, 0.3 mL $L^{-1}$ water) is an adequate antibacterial agent for many applications, but is not as effective or as long lasting as calcium selenate. However, chlorinated water solutions are generally adequate for the more rapid measurements obtained with the SSC-UFA method.

**Procedure.** Steady-state centrifuge methods rely on a sequence of runs whereby at each step, steady state is achieved and values of $K$, $\theta$, and $\psi$ (if desired) are determined. Information is obtained during drying if the sequence starts at saturation, or during wetting if it starts with a dry soil.

*Sample Preparation*. Samples may be cored in the field directly into the appropriate retainer for centrifugation, or oversized minimally disturbed samples may be taken in the field and subsequently recored. For some applications, especially where reproducibility for experimental purposes is more important than correspondence of measured properties with those of in situ soils, artificial repacking is necessary. This is best done with a machine designed to pack samples to the desired bulk density with negligible segregation of particles by size or other characteristics (Ripple et al., 1973). For applications where less uniformity and quality is acceptable, bulk samples may be hand packed into the appropriate retainer by a fill and tamp (American Society for Testing and Materials, 1999) or slurry method.

*Planning the Sequence of Runs*. $K$ can be determined over a range of desired water content values by choosing appropriate flow rates and centrifuge speeds. The choice of parameters will fix the range of $K$ values to be examined. An initial $K_{\mathrm{sat}}$ determination will give an indication of the maximum flux to apply during a sequence of unsaturated runs. If $K_{\mathrm{sat}}$ is relatively low, the driving force at the wettest run in the sequence must be sufficiently high and the flow rate must not exceed the measured $K_{\mathrm{sat}}$ inflow. Starting with a saturated sample, a stepwise decrease in the inflow rate using a precision metered pump or ceramic plate with known flow properties, along with a chosen rotational speed, allows measurement of the primary drying curve. Finer samples may need to start at relatively low flow rates, not exceeding $K_{\mathrm{sat}}$, and be run at high speed, while coarser samples may start at higher inflow rates and be run at lower speed.

In most cases of unsaturated SSC measurements, the $K$ value that will be obtained in a given experimental run is essentially fixed by the choice of operating parameter values. Thus the purpose of each run is first to ascertain that the steady-flow conditions (and the nearly uniform profile conditions if desired) can be achieved, and second to obtain the $\theta$ and $\psi$ measurements that correspond to the established value of $K$. Equation [3.6.1.1–8] or [3.6.1.1.–11] can be used to estimate values of $K$ that will be obtained in a run.

The choice of centrifuge speed depends on the characteristics of the sample and the desired range of $K$ and water content to be explored. The two primary considerations are the driving force acting on the water and the compressive force acting on the solid medium. The most basic consideration is that the centrifuge speed must be great enough so that the centrifugal driving force is the major component of the net driving force. This is in contrast to the condition of $q \ll K$, in which the left side of Eq. [3.6.1.1–9] would be essentially zero. In that case, the forces would nearly balance and the profile would be essentially that of the hydrostatic case with the parabolic shape described by Eq. [3.6.1.1–10]. This condition would make it impossible to determine $K$ accurately from a SSC measurement because the total driving force is a difference of two terms nearly equal in magnitude, one of which ($\mathrm{d}\psi/\mathrm{d}r$) is poorly known. To prevent this problem, both the speed and the input $q$ should be set higher. This will increase the centrifugal force relative to $\mathrm{d}\psi/\mathrm{d}r$. In other words, the centrifuge speed must be great enough so that $q$ is not negligible relative to $K$. The speed required to accomplish this is generally greater for finer-textured soils (Nimmo et al., 1994). Normally it is desirable to substantially exceed the basic speed minimum to assure that Eq. [3.6.1.1–11] applies. The criterion for this is that the centrifuge speed must be great enough so that $q$ has a much larger magnitude than $K$. If speeds this high are not possible, lower speeds can be used as long as they exceed the basic minimum, though Eq. [3.6.1.1–8] will apply rather than Eq. [3.6.1.1–11], as will be explained in the section on calculations.

If the centrifuge compresses the samples compared with their in situ condition, it will change the hydraulic properties at least slightly. The effect of centrifugal compaction on the hydraulic property measurements depends on the medium and the water content range of interest. This effect may be negligible, it may impose an upper limit to the running speed, it may increase the range of uncertainty associated with the results, or it may require correction when results are calculated (Nimmo & Akstin, 1988; Nimmo et al., 1994). Coarse-textured soils and low water contents exhibit the smallest effects. In practice, compaction effects may be negligible for sands and for finer-textured soils if water content values are not very high. For finer-textured soils at saturation, compaction is more likely to affect the results, for example, the factor-of-four correction worked out by Nimmo et al. (1994) for a silty medium.

*Achieving and Testing for Steady State.* Each run must be carried out sufficiently long to achieve steady-state flow throughout the sample. One criterion is for the sample mass, and therefore the water content, to remain constant over time. Another criterion is that the in- and outflow rates should be equal, as determined from the prescribed pump rate (UFA) or the change in mass of the water in the inflow reservoir weight (IFC) and the change in the mass of the water in the outflow reservoir. If the centrifuge has a strobe light assembly and viewing port, the water level in the outflow reservoir can be monitored as the rotor is spinning to determine if the in- and outflow rates are equal. The time to achieve steady conditions may range from 1 h for high $K$ values, to one or more days for low $K$ values. For measurements on a series of samples that do not differ greatly in their hydraulic characteristics, it may be possible to develop a set program of run lengths coordinated with a sequence of $K$ values. This program can then serve as a guideline for run lengths on the remaining samples.

The sample is weighed at the end of each run and oven-dried after the last run to compute the water content corresponding to each steady-state measurement. The tensiometer (or alternative method if $\psi$ is outside the tensiometer range) may be used after each run to obtain a matric potential value for each established steady-state water content.

*Calculations and Software.* For the case of negligible $\psi$ variation in the sample, $K$ can be calculated directly from Eq. [3.6.1.1–11]. The sample midpoint ($r$ = 8.7 cm for UFA and ~18 cm for IFC) is generally used in this calculation, being approximately the point of average $\psi$, $\theta$, and centrifugal driving force. For cases where it is not yet known whether the $\psi$ gradient is significant, a numerical model of unsaturated flow in a centrifugal field can furnish useful information about matric potential profiles, $\psi(r)$, and driving forces to help in resolving this issue. The code used by Nimmo et al. (1994) uses a fifth-order Runge–Kutta algorithm with adaptive step size control (Press et al., 1989) to solve Eq. [3.6.1.1–8] for $\psi(r)$, given an estimated $K(\psi)$ function (represented by an empirical formula for convenience), the value of $q$ for the run in question, and the centrifuge speed $\omega$. The gradient $d\psi/dr$ within the sample can then be computed and compared with the magnitude of the centrifugal force. This comparison allows an evaluation of the run in terms of three categories: (i) the net driving force dominated by the centrifugal force, (ii) the net driving force significantly affected by both the matric potential gradient and the centrifugal force, and (iii) the net driving force insignificant because the centrifugal force and the matric potential gradient essentially cancel each other out. If the centrifugal force dominates, either Eq. [3.6.1.1–8] or [3.6.1.1–11] can be used to calculate the value of $K$ for the run; if both types of forces are significant, Eq. [3.6.1.1–8] must be used; and if the forces cancel each other out, the run is not useful for $K$ measurement and must be discarded. Experience with measurements on a variety of media indicates that the conditions of Category 2 or 3 are most likely to occur for dry conditions and low $K$ values, although they sometimes also occur for the wettest and highest $K$ runs when low centrifuge speeds are used.

To optimize the determination of $\psi(r)$ and $K(\theta,\psi)$, especially for those cases that fall into Category 2, the calculations can be repeated with a revised estimate of $K(\psi)$ that takes advantage of the newly computed $\psi(r)$. This revision of $K(\psi)$ is best done using results from all valid centrifuge runs for the sample in question. Unless all runs are dominated by centrifugal force, the next $K(\psi)$ (after $d\psi/dr$ is recomputed) will differ somewhat from the previous one. The updated $K(\psi)$ can in turn be used to again revise $d\psi/dr$ and recompute $K(\psi)$. Iteration, using a Newton–Raphson scheme, can quickly produce an optimal $K(\psi)$ and a best-estimate $\psi(r)$ for computing the best $K$ values to pair with the $\theta$ and $\psi$ measured after each run.

Regardless of which forces are significant, the computations require certain conversions of flow rate and driving force. Volume flux in milliliters per hour or cubic centimeters per hour must be converted to flux density ($q$) in centimeters per second by dividing by the cross-sectional area of the sample (8.55 $cm^2$ for the samples frequently used with the UFA rotor; 19.63 $cm^2$ for the 5-cm-diam. samples frequently used with the IFC apparatus). Centrifuge speed is usually known in revolutions per minute (rpm), which must be multiplied by a factor of $\pi/30$ to convert to radians per second to obtain angular velocity ($\omega$). For the driving forces and $K$ values it is usually desirable to convert the units so that they do not involve pascals as in Eq. [3.6.1.1–5] and [3.6.1.1–6].

### Discussion and Conclusions.

*Comparison of Steady-State Centrifuge Techniques and Apparatus.* The IFC and UFA systems have different features and capabilities. The UFA apparatus has the great advantage of being simpler to operate, typically requiring less than half as much time per measurement as the IFC apparatus. This advantage stems from the use of an easily adjustable pump to control the applied water flux. The UFA apparatus is commercially available, but costs several times as much as the IFC apparatus. For the latter, part is commercially available and part must be custom fabricated. The dimensions of the rotor and sample are significantly different. The UFA is limited to sample cylinders either 3 or 4 cm in diameter (depending on the rotor model), whereas the IFC normally accepts 5-cm-diameter samples and could be modified to handle much larger ones. Another significant IFC advantage is its greater radius of rotation of the sample (about 18 rather than 8 cm). The top of the UFA rotor sample retainer is 6.2 cm from the center of rotation, while the bottom is 11.2 cm from the center of rotation. This makes the maximum force achievable with the IFC more than twice as great as with the UFA. Additionally, the force field within the sample is much more uniform with the IFC than the UFA (varying by a factor of 1.8 from the inlet to the outlet face in the UFA and by about 1.2 in the IFC apparatus). Other points of comparison, such as the possible range of measurements, reliability of the controlled flux, and measurement uncertainties, generally require little attention. Future developments should include a much larger centrifuge, resulting in highly uniform force fields, and possibly internal metering pumps for flow control.

*Effects of Centrifugation on Measured Properties.* In most cases, the biggest concern with the use of centrifugal force is that compaction can alter the structure of the material so as to influence $K$ and water retention. For consolidated materials and media such as densely packed sands (Nimmo & Akstin, 1988), compaction may be negligible. For other cases, such as fine-textured or lightly compacted media, compaction and its effect on $K$ and water retention may be significant. However, it may be possible to correct for compaction effects. In going from 1 to 200 $g$, $K_{\text{sat}}$ for a compacted silt-loam-textured sample declined by a factor of four in the experiment of Nimmo et al. (1994). This might be a reasonable upper limit for the effect of centrifugation on unsaturated $K$ for comparable media and conditions. For some highly structured soils, however, centrifugal methods may be unsuitable altogether. On the other hand, for some applications, centrifugal compaction is advantageous in permitting $K$ to be measured under conditions of a simulated overburden pressure approximating that of the original condition of the sample. At accelerations of a few thousand $g$, a small mass placed on top of the sample can exert a mechanical pressure equivalent to that of hundreds of meters of overlying material. To simulate a given overburden, for greater uniformity of stress from the top to the bottom of the sample, it is better to use a large mass at low speed than a small mass at high speed. However, the speed must still exceed the minimum for a well-defined driving force as explained above. Nimmo et al. (1994) gave formulas and other considerations for generating effective overburden pressures. Differences in temperature between the laboratory and subsurface field conditions can also be minimized using a centrifuge with a controlled-temperature chamber.

A fundamental concern is whether the centrifugal force distorts air–water interfaces in ways that affect the hydraulic properties. The most directly applicable evidence is from the test of the unsaturated version of Darcy's Law by Nimmo et al. (1987), in which $K$ at a fixed value of $\theta$ did not vary significantly as the centrifugal force varied from 200 to 1650 $g$. In this test, then, any effect of the variable force on air–water interfaces was insignificant for $K$ determination.

*Hysteresis.* Soil water retention is subject to hysteresis as exhibited by different water content values, corresponding to the same matric potential, during drying or wetting situations. The sequence of measurements can either start from near saturation (drying curve) or from a low water content (wetting curve), as desired. Preliminary centrifugation with low or zero applied water flux can bring the samples to a desired water content state from which to begin a wetting curve. Usually, the time required to approach steady-state conditions for a run on a wetting curve is greater by a factor of two or so, compared with the time needed for a comparable point on a drying curve.

An issue related to hysteresis is its possible interference with the properties measured. During runs with significant $\psi$ gradients, the water content varies within the sample. When the centrifuge stops for sample weighing or other reasons, water within the sample will redistribute from wetter regions to drier regions, so that the different parts of the sample are on different hysteretic curves. In many cases, for example, at low $\theta$, where the retention curve has little sensitivity of $\theta$ to $\psi$, this effect should be negligible. In other cases, it should be kept in mind that the measured results are not perfectly representative of either a drying or a wetting curve.

*Conclusions.* The measurement techniques described in this section combine the advantages of simplicity and accuracy with the speed and versatility afforded by centrifugal force. In most techniques, the time required to measure an unsaturated $K$ value increases with decreasing water content. The use of centrifugal force permits a decrease in measurement time and/or an increase in the range of $K$ values to be determined. Like some gravity-driven methods (e.g., Section 3.6.1.1.a), it can operate in a way that yields nearly uniform water content distributions.

Steady-state centrifuge methods are useful in situations where compaction is not a serious problem or where it is desired to measure hydraulic properties with overburden pressures that approximate those under field conditions. They allow the body force to be set at a desired value, both for establishing a conveniently measured water flow rate and for simulating a desired overburden pressure on the sample.

Steady-state centrifuge methods can measure $K(\theta)$ of samples with various textures across a wide range of $K$ values that are important in applications such as the determination of deep percolation or aquifer recharge rates. Targeting of a specific water content for a certain application is aided by the ability of the SSC method to generate measurements quickly, to adjust the $K$ to be measured, and to know the approximate values of both $\theta$ and $\psi$ while a series of measurements is in progress.

### 3.6.1.1.f References

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flowing into macropores during bypass flow occurred through films of water along the macropore walls. The number and length of the films were strongly related to the amount and intensity of the applied rainfall. The development of new films, and the creation of new initial infiltration areas, is important at low intensities. At high intensities, because of the fast propagation of the macropore-wetting front, the potential capacity available for developing new films is small.

4. Linear outflow. In the time span between $t_s$ and $t_e$, the outflow is nearly linear ($t_{\text{lin}}$ in Fig. 3.6.1.1–10). A quasi steady-state condition is thus suggested between the absorption processes and the applied rainfall intensity. During this steady-state period, outflow can be expressed as a fraction of the inflow, thereby quantifying the absorption of bypass flow water into the soil matrix. Booltink et al. (1993) related this bypass flow characteristic to morphological features such as fractal dimensions and volumes of methylene blue stained macropores.
5. Total outflow. Cumulative total outflow at the end of the experiment can be correlated to the time lag for initial breakthrough $t_c$ (Hatano & Booltink, 1992). At low rainfall intensities, the time of initial breakthrough is much larger, as compared with high intensities, but this effect is compensated for by the duration of rainfall.

**Comments.**

1. The experimental setup provides a simple and flexible measuring system and can measure bypass flow rapidly. Data obtained can be used for a physical and morphological characterization of the flow system. It can also serve as input in simulation models to predict bypass flow phenomena (e.g., Booltink, 1994)
2. The method can easily be combined with other physical and morphological analyses. Bouma and Dekker (1978) and Bouma et al. (1981) used a simple version of this method for field studies of infiltration in heavy-textured soils in the Netherlands. Hatano et al. (1992) linked fractal dimensions of stained flow patterns with chloride breakthrough in various volcanic soils. Booltink et al. (1993) used this method to analyze and combine bypass flow phenomena with soil morphological features, whereas Crescimanno et al. (1999) applied the method to study the effects of salinity on bypass flow.
3. Important elements of successful application of the method generally go back to sampling procedures. Disturbance of the soil structure during sampling causes nonrepresentative samples and leakage of the sample at the cylinder–soil interface.

### 3.6.1.1.f References

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