A fully-automated apparatus for the determination of three types of hydraulic conductivity

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Abstract. Knowledge of hydraulic properties, such as hydraulic conductivity and soil moisture retention, is crucial for understanding flow and contaminant transport in the subsurface. Hydraulic properties are often important input parameters for numerical simulation of flow and transport. Unfortunately, acquisition of these properties is usually time consuming and costly because of the manual labor associated with the currently available laboratory techniques. Lately, there has been increased interest in automating hydraulic conductivity laboratory techniques to reduce analysis time and improve data consistency. The newly designed fully automated Hydraulic Conductivity Apparatus (HCA), located in the Environmental Molecular Sciences Laboratory at Pacific Northwest National Laboratory, provides enhanced capabilities. The HCA is unique in that it is able to determine hydraulic conductivity with the falling head, constant head, and constant flux methods in a fully automated fashion. This paper demonstrates the new apparatus and presents hydraulic conductivity data for standard laboratory sands.

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1. Introduction

The rate of movement of water through porous media is of considerable importance to subsurface hydrology (Klute and Dirksen, 1986). One of the properties controlling the behavior of water flow in the subsurface is hydraulic conductivity, which is a measure of the ability to conduct water.

Hydraulic conductivity values of saturated soil columns (K_{sat}) are typically measured with constant head, falling head, and constant flux techniques. In the constant head method, the rate of flow is measured for a prescribed head difference. For this method, the K_{sat} (LT^{-1}) is computed according to Eq. (1):

$$K_{sat} = \frac{QL_c}{A_c \Delta H} \tag{1}$$

where Q is the observed flow rate (L^3T^{-1}), A_c is the column cross-sectional area (L^2), L_c is the length of the porous medium in the column (L), and ΔH is the imposed head difference (L). In the falling head method, the soil column conducts water according to a decreasing head in a standpipe with cross-sectional area A_s (L^2). The K_{sat} for this method is computed as follows:

$$K_{sat} = \left(\frac{A_s L_c}{A_c t}\right) \ln\left(\frac{H_1}{H_2}\right) \tag{2}$$

where t (T) is the time for the hydraulic head to fall from level H_1 to level H_2 (L). In the constant flux method, water is injected with a certain rate and hydraulic head measurements are obtained by pressure transducers connected to tensiometers, or with manometers at two or more internal locations. The K_{sat} representing the zone between two locations where hydraulic heads are obtained is computed according to:

$$K_{sat} = \frac{QL_p}{A_c \Delta H_p} \tag{3}$$

where L_p (L) and ΔH_p (L) are the distance and hydraulic head difference, respectively, between the two locations where the hydraulic head data are obtained. Detailed descriptions of the falling head and constant head methods can be found in Klute and Dirksen (1988). A methodology for constant flux measurement, including the use of pressure transducers, was described by Schroth et al. (1996).

Acquisition of K_{sat} data is usually time-consuming and costly because of the manual labor associated with the currently available laboratory techniques. Lately, there has been increased interest in automating hydraulic conductivity laboratory techniques to reduce analysis time and improve data consistency (e.g., Johnson et al., 2005). The newly designed fully automated Hydraulic Conductivity Apparatus (HCA), located in the Environmental Molecular Sciences Laboratory at Pacific Northwest National Laboratory, provides enhanced capabilities. The HCA is unique in that it is able to automatically determine hydraulic conductivity using the three major techniques (falling head, constant head, and constant flux) and the manner water is forced to move in a nominally one-dimensional direction. This paper demonstrates the new apparatus and presents hydraulic conductivity data for standard laboratory sands. In addition, a comparison of data obtained using the HCA and constant head data using a traditional Tempe-cell are also included.

2. Methods

A schematic of the HCA is shown in Fig. 1. Both repacked and undisturbed columns can be used in this setup. In this paper, results of 20-cm long repacked columns with an internal diameter of 5.08 cm (corresponding to a cross-sectional area A_c of 20.27 cm^2) are discussed. Two tensiometers, attached to Heise Model DXD pressure transducers (Ashcroft Inc., Stanford, CT; PT1 and PT2 in Fig. 1), are located at 5 cm from the top and bottom resulting in a distance L_p of 10 cm. The column design is unique in the way water is allowed to move into and out of the porous medium. By using relatively large inflow and outflow reservoirs, no multidimensional flow patterns are created in the porous media, even for highly conductive materials.

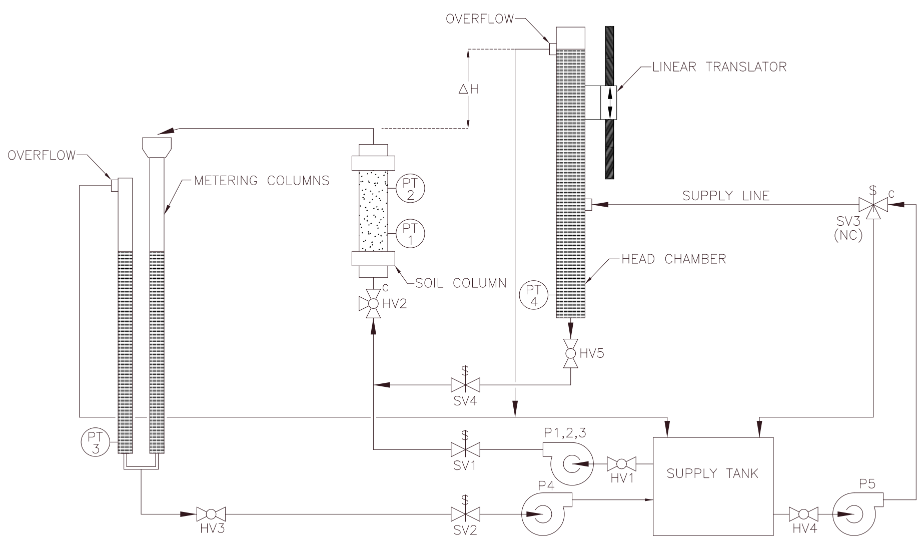

Figure 1. Schematic of Hydraulic Conductivity Apparatus (HCA).

A combination of three high-precision Encynova (Car-May LLC, Greeley, CO) metering pumps (P1, P2, and P3 in Fig.1) is used for the constant flux tests. When the imposed rate is less than 1 cm^3/min, only P1 is used. For rates larger than 1 cm^3/min, each pump is allocated 1/3 of the total rate. The head difference ΔH for the constant head method, and the initial head H_1 for the falling head method are obtained by manipulating a linear translator (Intelligent Motion Systems, Inc., Marlborough, CT) connected to a 60-cm-long cylindrical head chamber with a diameter of 5.08 cm. As a consequence of this diameter choice for the head chamber, the cross-sectional areas in Eq. (2) cancel out.

After packing the column under saturated conditions and subsequently mounting it on the HCA, the user then initiates the acquisition program, written in LabVIEW (National Instruments Corporation, Austin, TX). Besides general information about the column, date, and time, the user is prompted to enter an estimate of the porosity, obtained when packing the column. The column is then flushed for five pore volumes using the constant head setup shown in Fig. 1, with a ΔH of 10 cm. Outflow is directed to a metering column, which is drained after each flushed pore volume, based on readings from PT 3. After this flush, solenoid valve 4 (SV4) is closed and PT 1 and PT2 are set to zero. Deaerated water containing 0.005 M $CaSO_4$ with trace amount of thymol was used in the experiments.

Before the actual K_{sat} measurements are started, a "smart search" of the column is completed to provide an estimate of the K_{sat} value. The goal of the search is to find an injection rate Q, corresponding to a unit hydraulic head gradient between PT1 and PT2. The search starts by injecting a rate of 0.1 cm^3/min and recording the hydraulic head at PT1 and PT2 for five seconds. If the pressure head difference between PT2 and PT1 is less than 1 cm, the rate is increased by a factor 10. If the pressure difference is larger than 1 cm, the rate is increased by a factor 10 divided by the latest recorded head difference. This sequence is repeated until the pressure head gradient is between 0.9 and 1.1., and an estimate of the K_{sat} is then computed according to Eq. (3). Based on Fig. 28-6 in Klute and Dirksen (1986), the user is advised of what methods are typically used for the expected K_{sat}. The advised methods and ranges in K_{sat} are listed in Table 1. It should be noted that Klute and Dirksen (1986) recommended the constant flux test only for K_{sat} values > 10^{-7} cm/s. However, with the increased quality of the currently available transducers, this method can now be used for a much wider range of K_{sat} values. It should be noted that the information in Table 1 is only provided to guide the user who, at this point, has the choice to use either one, a combination of either two, or all three methods. At this juncture, the user is also prompted to enter the number of repetitions for each method and, if selected, the H_1 and final (lowest) H_2 values for the falling head method.

Table 1. Advised K_{sat} methods based on initial estimate.

K_{sat} estimate (cm/s)	**Recommended method**
> 10^{-3}	constant head; constant flux
> 10^{-3} and < 10^{-5}	constant and falling head; constant flux
< 10^{-5}	falling head; constant flux

Depending on the selection, the method sequence is always constant flux, constant head, and, finally, falling head. If the constant flux method is selected, the estimated K_{sat} value is used to determine injection rates. In this test, fluxes representing 0.2, 0.4, 0.6, 0.8, and 1.0 times the estimated K_{sat} value are used. The measured K_{sat} value for this method is derived from the slope of the head difference versus flux relationship used Eq. (3). An example is shown for a 70-mesh Accusand in Fig. 2. For this method, each sequence is repeated three times

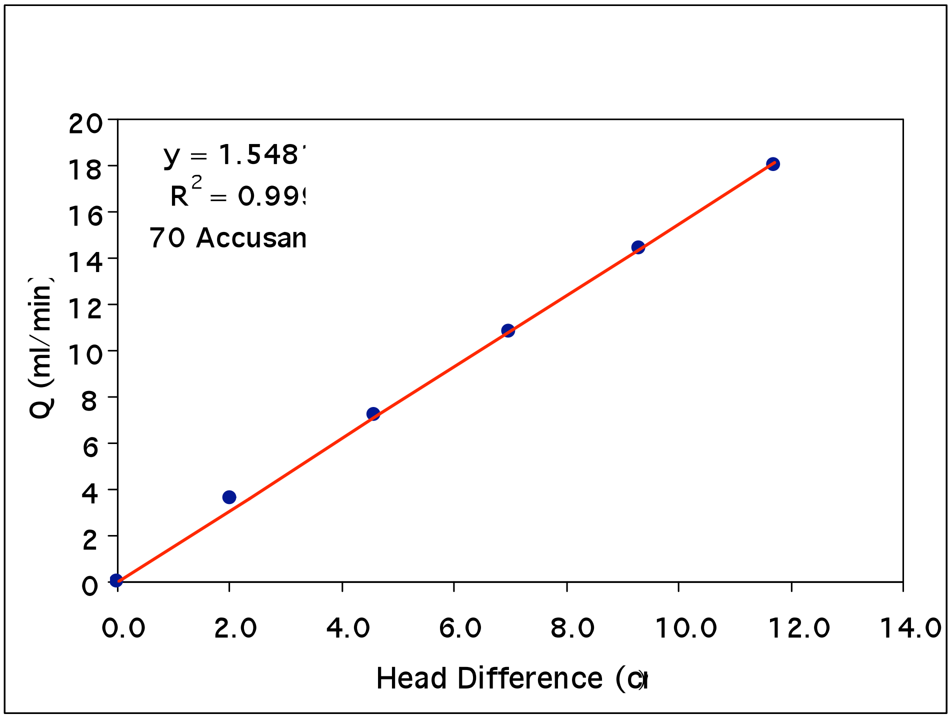

Figure 2. Example of constant flux output for a 70-mesh Accusand sample. The slope of the line is converted to a K_{sat} value.

For the constant head method, tests with head differences (ΔH) of 50 and 100% of the column length are used. The water that exits the column is collected in the metering column. The water elevation in the column is measured with transducer PT3 and converted to volumes. The slope of time versus volume relation is subsequently converted to a K_{sat} value. An example is shown for a 12/20 Accusand in Figure 3.

For the falling head test, standard procedure for each test is to start out with a pressure head H_1 equal to the length of the column. However, the user has a choice to select an initial head between 55 and 10 cm. The default final (lowest) H_2 value is 2 cm but, again, the user has the flexibility to choose a value between 50 and 2 cm. The pressure head during the falling head method is recorded with PT4 (Fig. 1) and converted to a series of K_{sat} values using Eq. (2). An example of the time-dependent pressure head data results for this method is depicted in Figure 4 for a 20/30-mesh Accusand. The associated K_{sat} values are shown in Fig. 5.

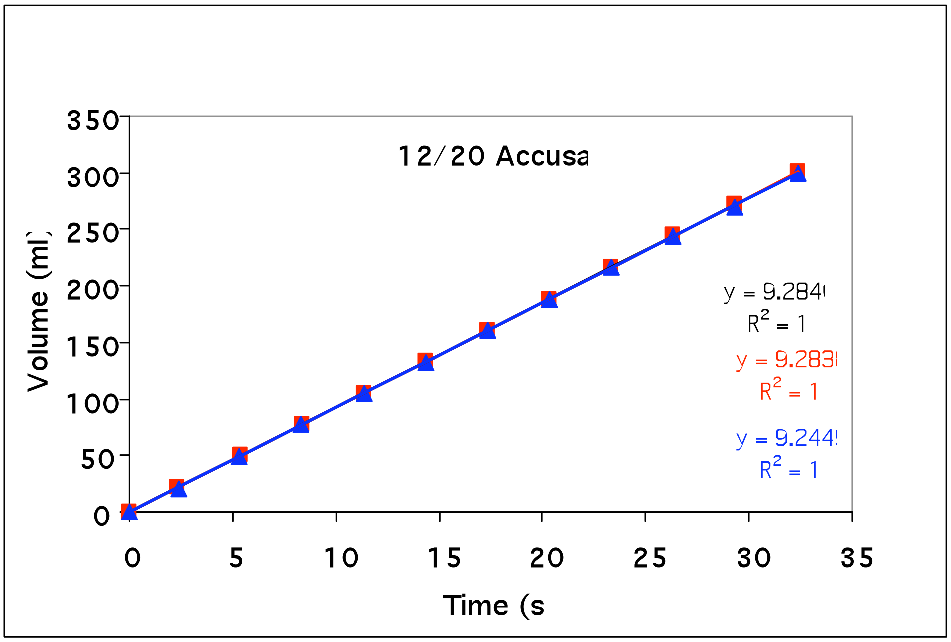

Figure 3. Example of constant head output for a 12/20-mesh Accusand sample. The slopes of the lines are converted to K_{sat} values using Eq. (1).

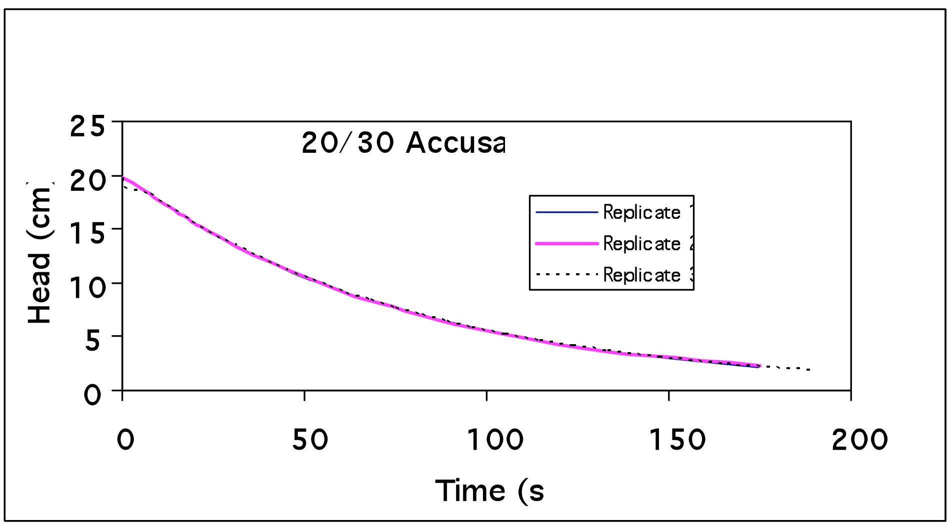

Figure 4. Example of falling head output for a 20/30-mesh Accusand sample.

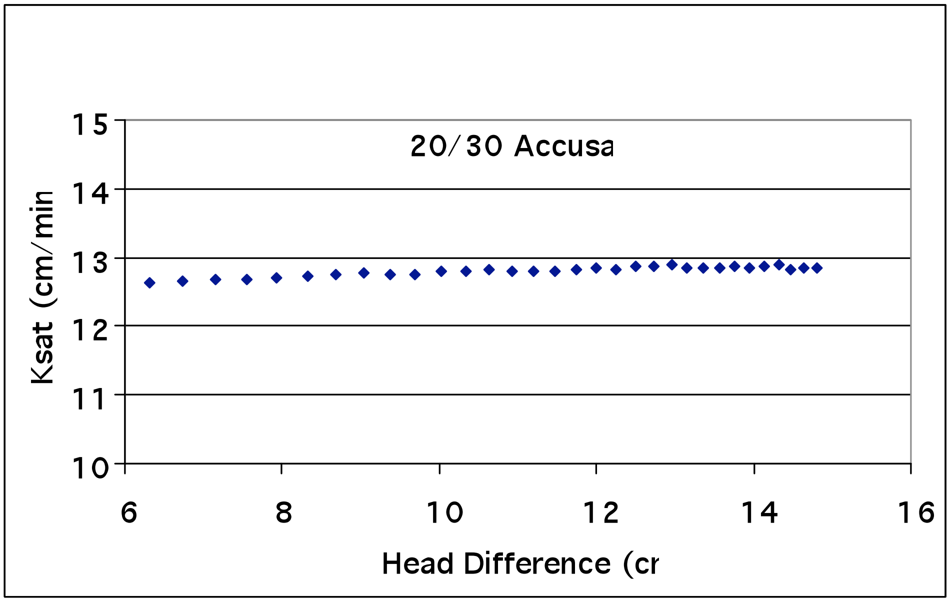

Figure 5. Computation of K_{sat} values for the falling head method using Eq. (2) and data presented in Figure 4.

3. Results

Constant flux, constant head, and falling head hydraulic conductivity (K_{sat}) experiments with 12/20, 20/30, 30/40, 40/50 and 70 mesh Accusand were conducted in 20-cm long columns. Three packings per porous media type were analyzed. The experimental sequence for K_{sat} measurements is constant flux, constant head, and falling head. Results obtained with the HCA, constant flux data from Schroth et al. (1996), and constant-head data using a traditional Tempe cell column are shown in Table. 1.

Table 1. Results of HCA tests, constant flux data from Schroth et al. (1996), and Tempe cell constant head data. All hydraulic conductivity data are in cm/min and are the averages of 3 packings and 3 repetitions. The constant head method data are for a 20-cm head difference.

Accusand Mesh Size	HCA Constant Flux	HCA Constant Head	HCA Falling Head	Schroth et al. (1996) Constant Flux	Tempe Cell Constant Head
12/20	30.9	29.2	26.2	30.2	16.2
20/30	16.4	16.1	12.9	15.0	9.3
30/40	8.5	8.2	7.5	8.9	4.6
40/50	4.0	3.8	3.5	4.3	2.3
70	0.8	0.7	0.6	n.d.	0.3

The HCA data show, that for this apparatus the constant flux method produced larger values than the other two methods, although the differences with the constant head method were rather small. Differences with the falling head method for all sands were larger and may be the result of remaining resistances in the system for this method. The constant flux method results obtained with the HCA and reported by Schroth et al. (1996) for the same Accusands were similar. The similarity in the results provides independent confirmation that the HCA functions properly. Of interest are the large differences between the HCA results and the results obtained using a method were the HCA end caps were replaced with traditional Tempe cell end caps. The experiments with the traditional end caps yielded apparent K_{sat} values that were up to ~50 % smaller than the values obtained by the HCA or by Schroth et al. (1996). The reduced values are primarily the result of bypassing of porous materials when the Tempe cell end caps are used.

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