LMECOL2002-001

Small Falling-Head Devices to Determine K_S in Porous Media

Aaron L. Mills, George M. Hornberger & Janet S. Herman

A publication of the Laboratory of Microbial Ecology
Department of Environmental Sciences
Clark Hall
University of Virginia
Charlottesville, VA 22903

Abstract

Simple falling-head permeameters were constructed from 10-mL plastic syringes. Saturated hydraulic conductivity was determined for a series of small horizontally oriented cores taken from a larger vertically oriented core with the devices. The results were consistent with other measures of conductivity made at the site from which the samples were taken, and also were consistent with the pattern of travel of bromide tracer through the formation. The results suggest that the minipermeameters can be used to determine the distribution of hydraulic conductivity for purposes of interpreting and modeling flow and transport in unconsolidated saturated porous materials.

Introduction

At some point, nearly all hydrogeologic studies require some estimate of the hydraulic conductivity (K_s) of the porous medium under examination. Values often are derived from pump tests in wells, either open or packed off in sections, or from rising- or falling-head slug tests on wells. Borehole flow meters can also be used to obtain conductivities if the head gradients are adequately known. Occasionally, falling-head or constant-head tests are conducted on cores of the aquifer material to infer a hydraulic conductivity, although such measurements give an estimate of only the vertical K_s. The pumping and slug tests represent behavior over the entire screened interval, unless packers are used to isolate a specific section. In neither case can anisotropy ratios be inferred from the data, even though very impermeable layers may slow water movement through vertically collected saturated cores.

In order to examine the vertical distribution of hydraulic conductivity in cores of sandy aquifer material, we developed simple permeameters to sample unconsolidated sediments from cores and to measure the horizontal conductivity at various depths in the cores by means of simple falling head tests. The results suggest that the approach can be used to examine the vertical distribution of horizontal KS within a core, although there may be a bias in the actual values obtained for the saturated hydraulic conductivities obtained with the devices.

Methods

Construction of the Sampler/Permeameter:

Falling-head conductivities were determined in small sub-cores collected from larger cores obtained during the installation of wells in a field in the Coastal Plain of the Eastern Shore of Virginia. The sampler-permeameters were constructed from 10-mL plastic disposable syringes. The plungers were removed from the syringes, and the black rubber piston was removed from the tip of each plunger. A hole was drilled in the plastic disk at the end of the plunger to permit a length of 1/8” vinyl tubing (e.g., Tygon) to pass through with a snug fit so that no leaking occurred. (A number 22 or 23 drill works well.) A hole was also drilled through the black rubber plunger cap, the cap placed back on the end, and a 12-14" long piece of thin vinyl 1/8" tubing was passed through the plunger. The tubing was passed through the hole in the rubber cap which was replaced on the plunger tip. The tubing was then positioned to be flush with the cap. (See Figure 1 for detailed drawing). The tips were removed from the syringe barrels with a sharp knife or fine saw. Any plastic burrs from the cutting were removed with a sharp blade. Pushing a spare plunger through the syringe barrel helped to remove shavings from the inside of the syringe.

Using epoxy putty, a small piece of nylon mosquito netting was attached to the plunger cap. When the epoxy cured, the plunger was put back into a de-tipped syringe barrel. End plugs for the samplers were constructed of rubber plunger caps (taken from additional syringes) with a hole bored into them. A length (12-14") of the vinyl tubing was glued into this hole. (A material called Plumber’s Goop works well for this step.) After the glue dried, scissors were used to cut the tubing flush with the plunger cap. A piece of the mosquito netting was fixed to the bottom of the tubing with epoxy putty as described above.

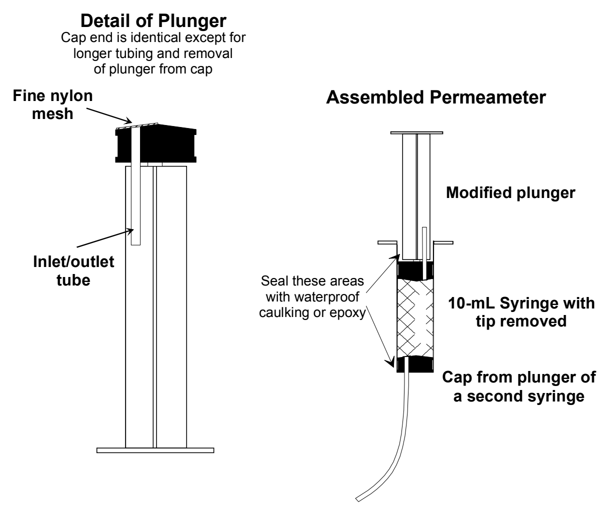

Fig. 1. Construction of the syringe minipermeameters. Dimensions and materials are given in the text.

Sample Collection:

Subcore samples were collected from intact core sections still in acrylic liners (5 cm diameter or greater), or when the core diameter was large enough (at least 7.5 cm), from cores that had been split for examination. For each sample to be collected from an intact core, a hole was bored through the lining at the sampling point. Use of a hole saw as opposed to a drill, minimized the disturbance of the core material (For thin-wall liners, a sharp bladed knife can be used to open a hole). The syringe was pressed into the core as far as possible while simultaneously withdrawing the plunger (so no large void space was left in the syringe). A consistent rotation on the syringe while applying pressure to the sampler helped to avoid the creation of small inconsistencies along the syringe wall resulting from insertion with a reciprocal twisting motion. For split cores, the samples were collected from the exposed face on the centerline of the core to the outer edge still held in the liner. In most cases, the samples collected were 3.5 to 4.5 cm in length. After the sample was collected, the rubber cap with the large tube was used to seal the open end of the syringe; the cap was secured with the Goop. If open air spaces were observed in the core, the samples were compressed slightly to eliminate the gaps without disturbing the structure of the intact portion of the sample (such action was unnecessary in samples from the saturated zone). Both ends of the tubing were clamped, using caution not to crimp the tubing with the drying glue, as this could cause a reduced inlet-tube circumference.

Hydraulic Conductivity Determinations:

In the laboratory, the samples were saturated with water by applying a gentle suction (as by mouth) to one end of the tubing, with the other end submerged in water. The samples were gently compressed again, and the plunger glued in place with Goop. The plunger end was completely sealed off with the glue, and the capped end was resealed if necessary. (It is important to find and seal all leaks at this step. Samplers with leaks will not completely saturate, and small air bubbles will continue to come through the leak when suction is applied.) As the glue dried, the samples were gently compressed periodically, a step important for an accurate measurement of sample length. Note that all compression steps were done only to remove visible voids that occasionally appeared during assembly of the permeameters.

When the seal dried, the syringe was flushed with at least 3 pore volumes of CO_2, or until no water was expelled from the outlet end. This took approximately 10 seconds at a delivery pressure of 20 psi. Any missed leaks were evident at this point and were resealed if necessary. The syringe and tubing were resaturated with water immediately, and the conductivity tests were run.

The syringe sampler containing the sand core was placed in line with another syringe (Figure 2.) for the purpose of making the falling head measurements. The test consisted of measuring the time required for the water level in the source syringe to drop a measured distance (H_0 - H_1). At least three such measurements were made for each syringe. Analyses were done with the syringe completely vertical. Theoretically, this is unnecessary, but it allows for an accurate measurement of H_0 and H_1.

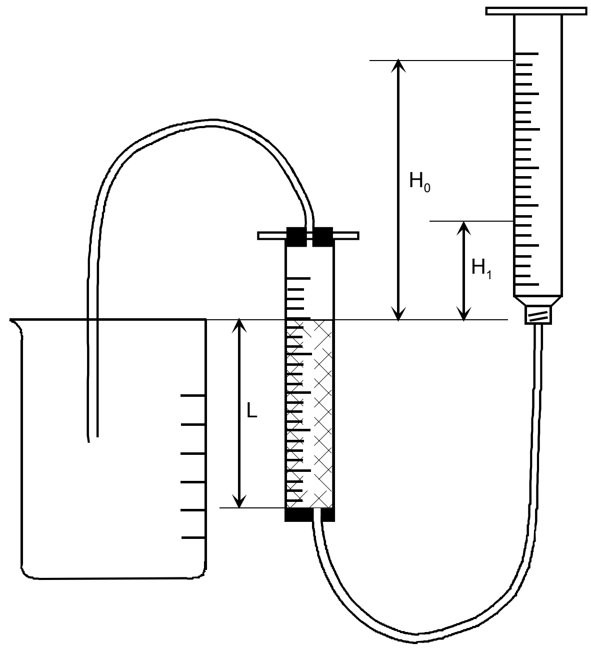

Fig 2. Application of the syringe minipermeameters in a falling head test. Measurements and calculations are described in the text.

Calculation of Saturated Hydraulic Conductivity:

The general equation for saturated hydraulic conductivity determined by the falling-head test is $K_S = A_t/A_c * L/T * \ln(H_0/H_1)$, where A_t is the cross-sectional area of the falling head reservoir, A_c is the cross-sectional area of the sample chamber, L is the length of the sand column, and T is the time for the water level to fall from H_0 to H_1. Because $A_t = A_c$ in our tests, the equation reduces to $K_S = (L/T)* \ln(H_0/H_1)$.

Experimental Methods:

Lab Studies

To evaluate the reproducibility of the syringe permeameter method, a column of sand collected from a pit near Oyster, VA was packed in a 10-cm diameter column to a depth of 7.5 cm. This column first was saturated with CO_2 then saturated with water from the bottom. The inlet at the bottom was connected to a calibrated reservoir, and a value for K_S was determined using a falling-head test. Three tests were done and the results averaged. Subsequently, three subcores were taken (in a vertical orientation, parallel to flow in the column) with syringes as described above. Three falling-head tests were done on each subcore.

Field Studies

To examine the utility of the falling head minipermeameters in a field situation, samples were taken at frequent intervals from cores collected during the installation of a series of wells comprising a flow cell for experimental injections in the sandy coastal plain aquifer near Oyster, VA. Of the large number of cores and samples taken, two cores are of particular interest. Core B2 was recovered during installation of a well used for injection of tracers into a doublet flow cell (Herman et al., 1997), and core T5 was a core collected 4 meters directly downgradient from the tracer injection well. Subcore samples for minipermeametry were taken from split cores at 10-cm intervals as described above. After installation of the wells, a series of multilevel samplers was installed with sampling ports at 0.5 m vertical intervals (Herman et al., 1997). A tracer study involving the use of bromide (injected at 100 mg L^{-1} for a period of 48 h) was conducted. Samples were collected 6 times per day at each port in a vertical sampler array 0.5 m downgradient from the injection (see Herman et al. (1997) for details).

RESULTS

Laboratory Measurements

Hydraulic conductivities determined on syringe-subsamples taken from a homogeneously packed sand column in the laboratory were internally consistent (repeated measures on the same syringe-subsample did not vary) and were similar among the samples (Table 1). The syringe samples yielded values of hydraulic conductivity that were about 2.5 times lower than the conductivity of the larger column from which the samples were taken.

Table 1. Saturated hydraulic conductivity determined on a column homogeneously packed with sand from Oyster, VA and on 3 syringe-minipermeameter samples from that column

	K_S (cm sec^{-1})	S.D.[a]	K(column)/K(syr)
Column	0.0694	0	-
Syringes	0.0277	0.00386	2.54

[a]The standard deviation for the core is based on 3 successive falling head measurements on the same core. The standard deviation for the syringe samples is based on three separate syringe samples taken from the column. The time associated with each individual syringe sample is the mean of three successive measurements.

Field Measurements:

Measurements in several cores collected as part of the installation of flow cells for tracer test experiments at the Oyster field site revealed substantial differences in the vertical distribution of saturated hydraulic conductivity within each core (Figure 3). Two of the cores which were on the center line for tracer experiments (Well B2 was the tracer injection well and Well T5 was a core taken at a distance of 6.5 m down gradient from B2) showed a distinct layer of low conductivity at about 6.3 m, and another between 7.5 and 8.0 m (note that no core was recovered from well B2 below 7.5 m). The zones of lowest conductivity coincided with the zones of slowest travel of the bromide tracer, while rapid transport characterized the zones of highest conductivity with the exception of the high conductivity zone at 9.8-10 m depth. No Br^- above background concentrations was seen in the samplers at that depth, but Br^- was injected over the interval from the water table surface to 9.0 m (the depth of well B2), so that no signal would be expected below that depth. Although porosity was not determined for these individual samples, similar samples have yielded porosities on the order of 30% to 35%. Dividing the computed Darcy velocity (based on a length of 0.5 m and a measured gradient of 0.47) obtained with the measured values of K_S by an estimated porosity of 0.33 yields a calculated linear flow velocity. Comparing that value with the travel time at each layer determined as the time necessary for the tracer concentration to reach 50% of its maximum value, shows good agreement in the pattern of conductivity distribution, although the specific values do not coincide perfectly (Table 2).

Discussion

The use of syringe-minipermeameters allows determination of the distribution of horizontal conductivity in the vertical direction from core samples of unconsolidated material. All of the values of K_S obtained with the syringe devices in the packed column were lower than observed in the overall column. Furthermore all values of K_S obtained in the field cores were lower than those calculated based on

Table 2 Comparison of predicted velocity from minipereameters with observed travel time for Br^- in 1st multilevel sampler (L=0.5 m). Travel time is the number of hours required to achieve a tracer concentration equal to one half the maximum tracer concentration observed in that sampling port. A value of 0 indicates that breakthrough was not observed in that port at any sampling time

Depth m BGS	Ks cm sec^{-1}	q cm day^{-1}	Travel Time hr	Calculated Velocity cm day^{-1}	Observed Velocity cm day^{-1}	obs/calc
5.5	8.00E-03	27.66	24	83	200	2.4
6.0	5.94E-03	20.51	20	62	240	3.9
6.5	7.57E-03	26.16	0	78		
7.0	3.11E-02	107.33	10	322	480	1.5
7.5	5.29E-02	182.94	14	549	343	0.62
8.0	5.87E-03	20.3	34	61	141	2.3
8.5	2.88E-02	99.64	12	299	400	1.3
9.0	3.29E-02	113.81	0	341		

travel times of bromide in the field site. One explanation for the bias is that compression of the samples occurs during sampling and handling (some compression of the samples may occur while removing large voids as described in the methods). More care in handling the samples may minimize the compression and therefore the underestimate of the K_S; if the bias can be made constant by careful handling, a correction factor might be applied. The range of the bias in the present study was fairly narrow, however, usually between 1.5 and 3, suggesting that the observed patterns of conductivity are a reliable indicator of the presence zones of high or low hydraulic conductivity. It is interesting to note that the values of K_S reported here for the field cores (about 6×10^{-3} cm sec^{-1} to about 5×10^{-2} cm sec^{-1}) approximate the range of values obtained by Burger and Belitz (1997) (1×10^{-2} cm sec^{-1} to 2×10^{-2} cm sec^{-1}), who examined the horizontal distribution of conductivity in an outcrop of the formation from which the field cores were extracted about 500 m away. The techniques used were similar, except that Burger and Belitz used 5-cm-diameter cores instead of the 1-cm-diameter cores used in the present work.

The method of determining the vertical distribution of horizontal saturated hydraulic conductivity presented here is not consistent with the standards set by ASTM (1967). Those guidelines require a 2¼ in dia core. Such cores are difficult to obtain in a horizontal direction, so what is measured is invariably the vertical conductivity, and that value represents the entire section of the core without regard to the distribution of more or less conductive horizons. It would be possible to use a section of core to determine vertical K_S and then subsample with syringes to "calibrate" the small-sample K_S from our method. Regardless of whether calibration is done, the technique described here can be used to infer a spatial pattern of K_S and this might be very useful.

Acknowledgements

This work was supported by grant # DE-FG05-89ER60842, from the Subsurface Science Program of the U.S. Department of Energy. Logistical support for field collections and access to the site was provided by the Virginia Coast LTER Program. Jim Saiers, Jennifer Nalbone, and Jeff Furr provided technical assistance for this work.

References

Burger, R. L., and K. Belitz. 1997. Measurement of anisotropic hydraulic conductivity in unconsolidated sands: a case study from a shoreface deposit, Oyster, Virginia. Water Resour. Res., v. In press.

Herman, J. S., A. L. Mills, and G. M. Hornberger. 1997. Sulfate as a reactive tracer in a sandy coastal plain aquifer. In preparation.

ASTM, 1967, Permeability and capillarity of soils: Philadelphia, PA, American Society of Testing Materials, 210 p.

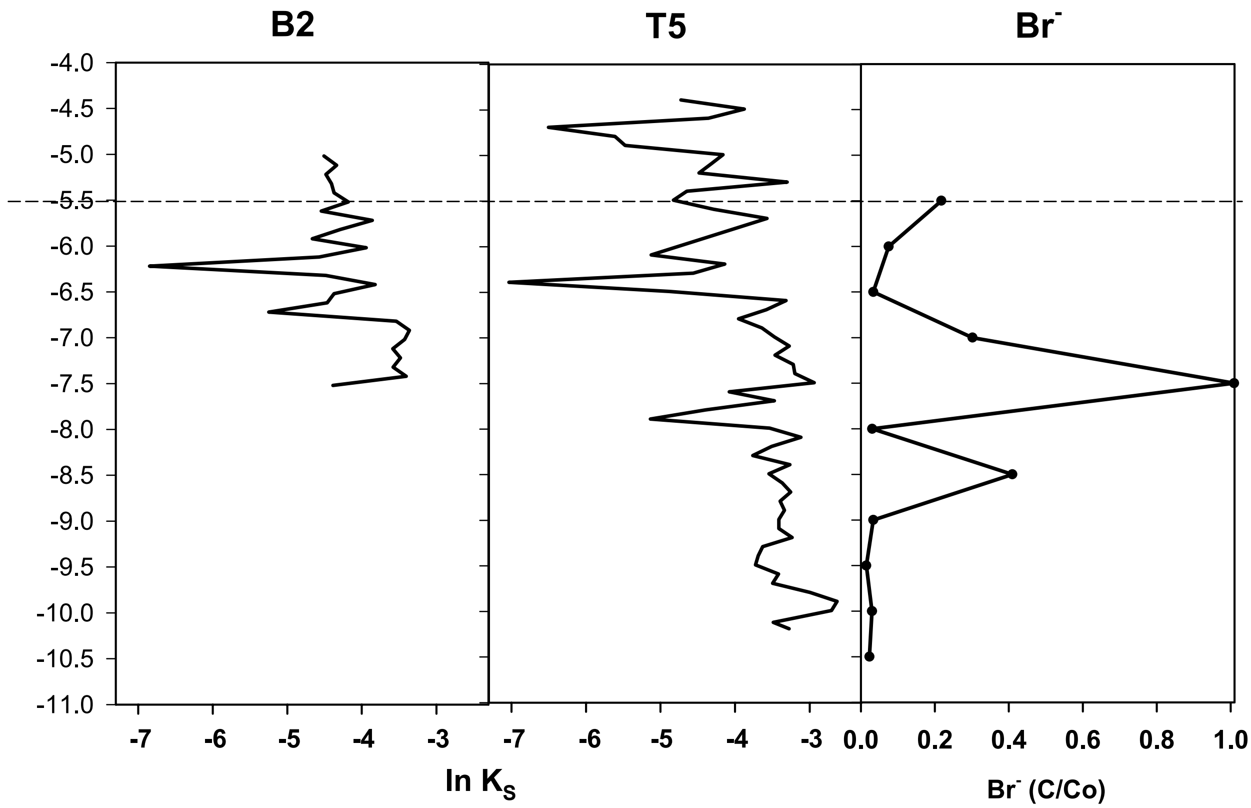

Fig. 3. A comparison of the measured conductivities taken at 10-cm intervals in two cores from a flow cell at the Oyster field site, with actual Br- tracer data collected 24 h after injection of the tracer at a multilevel sampler with ports at 0.5 m intervals. The distance from B2 to the multilevel sampler was 0.5 m. Results for depths greater than 7.5 m from well B2 were not obtained due to inability to recover the core intact. Bromide was injected in Well B2 which was only 9 m in depth, therefore there was no Br- above background below that depth in the multilevel sampler.