AUTOMATION OF A FALLING HEAD PERMEAMETER FOR RAPID DETERMINATION OF HYDRAULIC CONDUCTIVITY OF MULTIPLE SAMPLES

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Abstract

Measuring hydraulic conductivity of saturated soil (K_s) is one way to quantify soil hydraulic properties. However, this technique is very time consuming for both in situ and laboratory measurements, and often one is limited to measuring only one sample at a given time. Automation of hydraulic measurements has been suggested, but this has not been done for laboratory K_s measurements. Thus, we propose to use pressure transducers to measure K_s in multiple soil cores with a falling head permeameter. To accomplish this, an automated falling head permeameter was developed by attaching pressure transducers to falling head permeameters to measure K_s of soil cores in the laboratory and a datalogger was used to record the readings. To test this method, 64 soil core samples were taken from two locations, 30 from a sandy soil, 23 from a silt loam soil, and 11 from a silty clay loam soil. The automated unit allows for six samples to be processed with minimal human oversight compared with only one sample being read manually (conventional method), requiring frequent observations during a period often >30 min. When values obtained using the automated method were compared with values obtained for the same cores using the manual technique, there was no statistical difference at the 95% level.

Hydraulic conductivity of saturated soil is one of many methods for assessing water flow in soils, but this is known to vary considerably even at small scales (Nielsen et al., 1973). To aid in evaluating K_s when a large number of soil cores have been collected, we have focused on developing a simple automated technique to determine $K_{s.}$ The need for processing a large number of samples has precipitated modification of a set of falling head permeameters to make multiple measurements by measuring the head with pressure transducers and storing the data with a datalogger.

Numerous studies have been conducted to determine K_s in the laboratory as well as in situ. Although field techniques are generally more reliable than laboratory techniques (Klute and Dirksen, 1986; Reynolds and Elrick, 2002), the focus of this paper will be the latter, because in situations where a large number of samples need to be analyzed, laboratory techniques are more efficient. There are three general methods used to determine K_s in the laboratory, including the falling head, constant head, and no-discharge permeameters. The constant head permeameter, devised by Meinzer in 1923, (Stearns, 1928, p. 144–147) measured the rate of flow of water through columns of porous materials under low heads (Wenzel, 1942). This permeameter was designed along the same principles as Darcy's design in 1856. Theis (1934) developed the variable-head discharging apparatus (referred to here as the *falling head* permeameter) for groundwater investigations. The K_s was determined by monitoring the diminishing water level in a manometer. The no-discharge permeameter, developed by Meinzer (1923), made permeability measurements under very low hydraulic gradients (Wenzel, 1942). The difference between the water level in the supply and receiving reservoirs was observed across time.

The purpose of this study was to automate a falling head permeameter by implementing pressure transducers at the base of multiple falling head devices and recording changes in pressure (head) across time with a datalogger. It should be noted that this is not the first use of pressure transducers for water flow measurements. Most of the other measurements, including Constantz and Murphy (1987), Ankeny et al. (1988), Prieksat et al. (1992), and Casey and Derby (2002), used pressure transducers to automate and/or improve Mariotte reservoir systems in various applications ranging from tension infiltrometer to single ring infiltrometer measurements. Overman et al. (1968), on the other hand, used pressure transducers to measure K_s. The design presented in this paper is a modification of the apparatus that Theis (1934) developed. On the basis of our review of literature, there are three other cases of automated or rapidly measured hydraulic conductivity of disturbed soil cores reported (Overman et al., 1968; Nightingale and Bianchi, 1970; Wilson et al., 2000). The first such experiment was a falling head, but it was designed to measure slow flow rates (low K_s values) through porous material, which is contrary to the wide assortment of materials used in this study. This was a permeameter equipped with a pressure transducer and a closed stopcock to apply the initial head of water; subsequently, once the stopcock was opened, the pressure transducer measured the decreasing head across time, which was then used to calculate K_s (Overman et al., 1968). The second experiment was of the falling-head type, but a cell was used as an alternative to the usual vertical tube for water supply. The cell (referred to as a strain gage permeameter) measured water pressure displacement characteristics including changes in volume. The strain gage permeameter accurately measured the falling head-time relationship needed to calculate K_s of slowly permeable materials (Nightingale and Bianchi, 1970). Wilson et al. (2000) developed a semiautomatic falling head permeameter that used infrared emitters and detectors to measure the flow rate. They suggest that this permeameter is most suitable for measuring K_s in granular solids with high flow rate. On the basis of our literature review, the automation of a falling head permeameter has never

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Published in Soil Sci. Soc. Am. J. 69:828–833 (2005).
doi:10.2136/sssaj2004.0014N

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Abbreviations: K_s, hydraulic conductivity of saturated soil; LWRV, Lower Wisconsin River Valley.

been applied for multiple sample processing on undisturbed soil cores; thus, this is the objective of this study.

Materials and Methods

For this experiment, there were a total of 64 cores analyzed, 30 from a site in the Lower Wisconsin River Valley (LWRV) dominated by Sparta sand (uncoated, mesic Typic Quartzipsamments), and 34 from a site near Lancaster, WI, which consists of the soil series Dubuque silt loam (fine-silty, mixed, superactive, mesic, Typic Hapludalfs). To analyze soil samples, six permeameters were constructed from plexiglas and placed on a wooden support stand that was 0.9 m tall and 1.2 m long (Fig. 1). The stand has an 11-gauge expanded steel wire mesh base to support the soil samples. In an intermediate position, between the metal wire base and the base of the stand, was a water collection tray (plastic rain gutter), which was 1.52 m long and 0.23 m wide. The collection tray was designed to channel outflow water from the soil cores to a disposal container. The permeameters were 90 cm high with a 3.1-cm standpipe diam. (Fig. 1). The bases of the permeameters were designed to accommodate 7.62-cm-diam. soil cores with varying height. For this study, cores 7.62-cm in diam. by 7.62-cm long were extracted from the field sites with a double-cylinder, hammer-driven core sampler that was designed for obtaining soil samples with minimal disturbance (Blake and Hartge, 1986). Silk screens were placed over the base of the cores and secured with rubber bands to keep the samples in place. An o-ring was placed within the base of the permeameters to ensure a firm fit between samples and the permeameter without water leaks. A 1.12-cm-diam. opening was drilled and tapped into the center of the base of the permeameter to allow the insertion of a pressure transducer via a plexiglass T-fitting (Fig. 1). The fittings were developed with two female threads and one male thread, which were placed into the 1.12-cm opening on the base of the permeameter. A Teflon stopcock was placed in the top female end of the fitting to allow for removal of air from the pressure transducer and associated fitting. The pressure transducers were fitted to the bottom female end of the T-fitting with a 45° angle to allow for air escape. The pressure transducers used were Omega PX236 pressure sensors (Omega Engineering, Incorporated, Stamford, CT)[1]. Output from these sensors is in millivolts ($\pm$100 mV full range, with 10-V supply/excitation) producing a positive signal with respect to positive pressure and negative signals with respect to negative pressures (Operators manual: PX236 series pressure transducer). These pressure transducers have a response time of 1 ms, which means that this is not a limiting factor in our measurements.

Automation

The pressure transducers were calibrated with air pressure by applying different pressures and vacuums, and a second calibration was made with a head of water. Calibration data from the water column, including millivolt output for each corresponding applied pressure, were analyzed with regression lines, producing R^2 values of $\approx$1.0. The pressure transducers were connected to a data logger to record their output values and record the regulated excitation 10 V (Lowery et al., 1986). In addition, the datalogger was programmed to record the voltage of the battery used (12-V battery used to supply current to the logger and the 10-V regulator) and room temperature. Each falling head device was placed over a sample that had been saturated with tap water at room temperature 24 h before measurement. Samples were filled with water and rubber stoppers were inserted into the falling head device until they were measured. All stoppers were removed as rapidly as possible following initiation of the datalogger. The falling head tubes were filled with water using a funnel connected to Tygon tubing (Saint-Gobain Ceramics & Plastics, Inc., Northboro, MA) that extended to the top of the soil core to prevent disturbance of the sample. The rate of fall was determined for each sample while filling the falling head tube. The datalogger sampling time interval was set based on this rate that varied from 5 s to 2 h according to the type of soil being analyzed. Pressure transducer output was converted into centimeters of water using the specific regression equation for each transducer. A correction value of 10.8 cm was added to each value to take into account the distance from the transducer to the outflow at the base of the permeameters (Fig. 1). These values and associated time steps were used to calculate K_s using a derivation of Darcy's law:

$$K_s = \{(aL)\ [A(t_1 - t_2)]^{-1}\}\ \ln(H_1\ H_2^{-1}) \qquad [1]$$

where a is the area of the standpipe (cm^2), L is the length of soil sample (cm), A is the area of the core (cm^2), t is time obtained from datalogger (s), and H_1 and H_2 are the pressure heads (cm) at times t_1 and t_2, respectively.

Execution intervals for the datalogger varied according to soil type. For coarse material (sand), the execution intervals ranged from 5 to 30 s. Finer materials required execution intervals anywhere from 2 min to 2 h, depending on the pore and pore size distribution.

To evaluate the use of pressure transducers to produce an automated method to measure hydraulic conductivity, the two techniques (the conventional and automated methods) were compared using 64 cores. The conventional technique requires an individual to manually read the change in head (H_1 and H_2) across time. A comparison was made with the conventional readings taken every 10 s and automated taken every 5 s. Cores from Lancaster, ranging from silt loam to silty clay loam, were analyzed simultaneously with both methods. This was possible because water conductance rates for these samples are slow relative to the sandy soil from the LWRV. According to Bouwer (1978), falling head permeameters are generally used for materials with relatively low hydraulic conductivity, whereas constant head permeameters are suitable for measuring K_s of highly permeable materials like sands and gravels. It should be noted that the falling head permeameter that Bouwer (1978) described had a very small standpipe, which allowed for isolating small changes in H. Falling head devices can be used for material with large K_s values ($>10^{-4}$ cm s^{-1}), but the standpipe must be scaled up, as we have done (Reynolds and Elrick, 2002). However, when the standpipe is large, it is still difficult to take consistent measurements on sand or gravel using the conventional falling head technique. Thus, it is certainly difficult to manually take readings on multiple permeameters at any given time for materials with large conductivity values, like sand and well structured fine textured soil with large macropores. It can be demonstrated that, with the use of pressure transducers at the bases of the permeameters with large diameter stand pipes, a large number of soil cores ranging from sand to clay textures can be measured simultaneously and readings can be taken rapidly.

Numerous K_s values were obtained for each of the 64 cores since all cores were evaluated across time. However, average of K_s values (averaged across time, then averaged for a given method) for each of the 64 cores from the automated and conventional methods were analyzed via a paired *t* test. The

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[1] Mention of company or product name does not constitute endorsement by the University of Wisconsin-Madison or USDA-ARS to the exclusion of others.

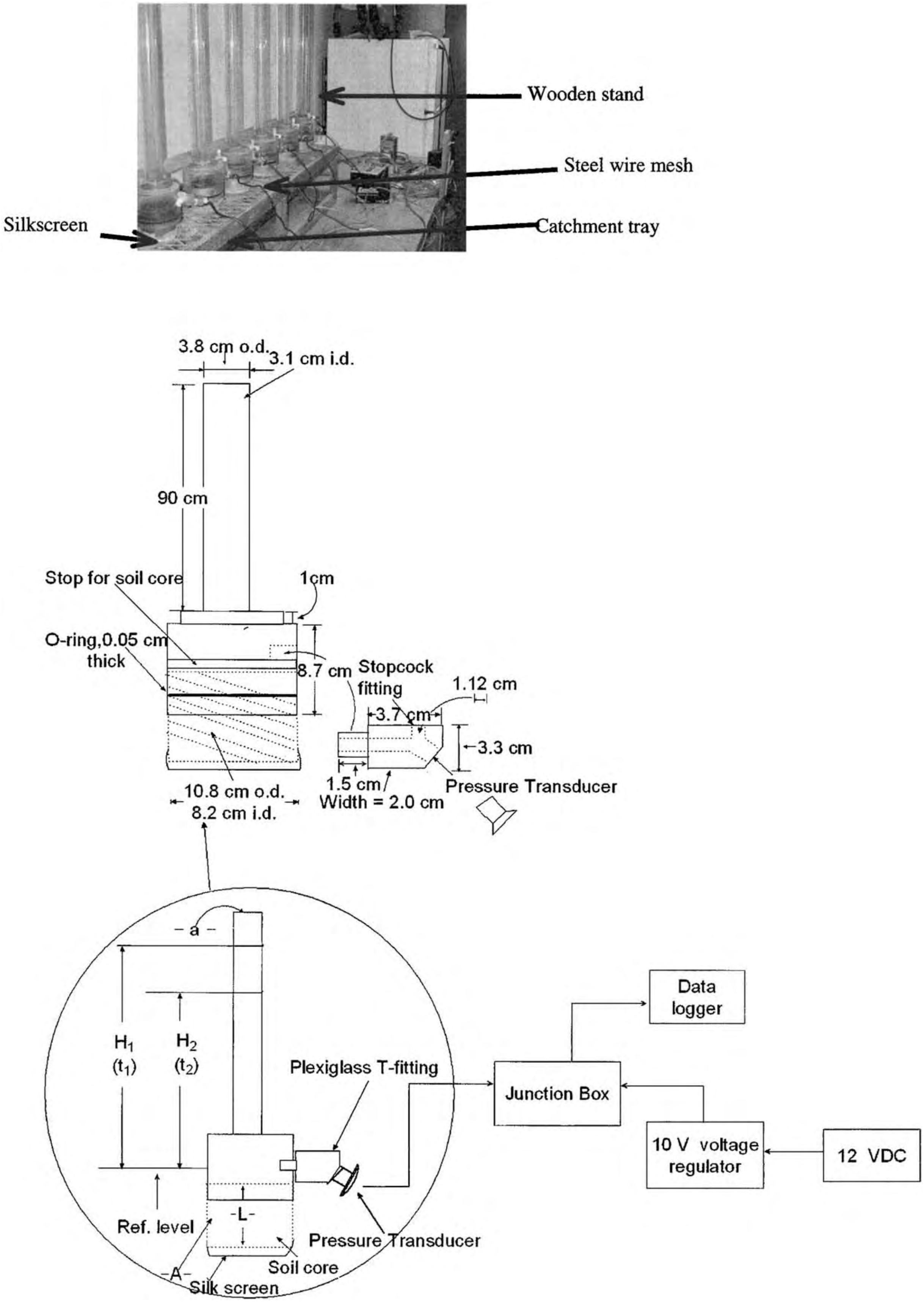

Fig. 1. Photograph and schematic representation of automated falling head permeameter including specifications.

Table 1. Hydraulic conductivity, averaged across time, for 30 sand soil samples using the conventional and automated methods.

	Sand	
Core	**Automated**	**Conventional**
	cm s^{-1}	
1	1.59×10^{-2}	1.46×10^{-2}
2	1.10×10^{-2}	1.30×10^{-2}
3	2.31×10^{-2}	2.34×10^{-2}
4	3.25×10^{-2}	4.24×10^{-2}
5	2.90×10^{-2}	2.56×10^{-2}
6	1.20×10^{-2}	1.62×10^{-2}
7	1.53×10^{-2}	1.33×10^{-2}
8	1.05×10^{-2}	1.24×10^{-2}
9	2.53×10^{-2}	2.50×10^{-2}
10	3.23×10^{-2}	3.53×10^{-2}
11	1.97×10^{-2}	2.22×10^{-2}
12	2.00×10^{-2}	1.49×10^{-2}
13	1.62×10^{-2}	1.52×10^{-2}
14	1.12×10^{-2}	1.22×10^{-2}
15	2.45×10^{-2}	2.38×10^{-2}
16	3.26×10^{-2}	3.83×10^{-2}
17	3.67×10^{-2}	4.05×10^{-2}
18	2.16×10^{-2}	1.61×10^{-2}
19	1.43×10^{-2}	1.28×10^{-2}
20	1.11×10^{-2}	1.22×10^{-2}
21	2.20×10^{-2}	2.16×10^{-2}
22	3.21×10^{-2}	3.65×10^{-2}
23	3.10×10^{-2}	3.39×10^{-2}
24	2.00×10^{-2}	1.50×10^{-2}
25	1.35×10^{-2}	1.23×10^{-2}
26	1.00×10^{-2}	1.16×10^{-2}
27	2.14×10^{-2}	2.12×10^{-2}
28	2.94×10^{-2}	3.42×10^{-2}
29	2.82×10^{-2}	3.37×10^{-2}
30	1.85×10^{-2}	1.43×10^{-2}
Average	2.14×10^{-2}	2.21×10^{-2}
SD	8.06×10^{-3}	1.00×10^{-2}
P value	0.88	

conventional method was used as one set of observations, and the automated method was the second set of observations. In addition, average K_s values of the cores from the three texture classes (averaged across time for each soil type) were evaluated by soil type for differences between the automated and conventional methods with a one-way ANOVA. Minitab (2002) was used for both *t* test and ANOVA analyses.

Results and Discussion

Average hydraulic conductivity values obtained using the automated and conventional (manual) methods, for soil samples representing different textures, using a falling head permeameter were not statistically different (Tables 1–3). The *P* values were 0.88, 0.78, and 0.92 for the sand, silt loam, and silty clay loam, respectively (Tables 1–3). Values for the 30 sand samples had an average K_s of 2.14×10^{-2} and 2.21×10^{-2} cm s^{-1} for the automated and conventional methods, respectively (Table 1). Average values for the silt loam soil samples (23 cores) were 1.48×10^{-3} cm s^{-1} for the automated method and 1.60×10^{-3} cm s^{-1} for the conventional method (Table 2). For the silty clay loam soil cores (11 samples), the values were 6.70×10^{-5} and 6.41×10^{-5} cm s^{-1} for the automated and conventional methods, respectively (Table 3).

Automated and conventional method K_s values for three representative cores, taken from the 64 total samples, for the three soil types evaluated were plotted as a function of time showing little difference between data for the two methods (Fig. 2A–4A). These plots demonstrate K_s values for soils representing sand, silt loam, and silty clay loam. Each graph for the three soil types yielded the same general shape when the two methods were compared (Fig. 2A–4A). The *P* values from a one-way ANOVA of the two methods for these example cores were 0.12, 0.94, and 0.75 for the sand, silt loam, and silty clay loam, respectively. This suggests that the two methods are not different.

Table 2. Hydraulic conductivity, averaged across time, for 23 silt loam soil samples using the conventional and automated methods.

	Silt loam	
Core	**Automated**	**Conventional**
	cm s^{-1}	
1	2.51×10^{-3}	2.74×10^{-3}
2	3.23×10^{-3}	3.69×10^{-3}
3	1.64×10^{-3}	1.87×10^{-3}
4	6.80×10^{-3}	7.22×10^{-3}
5	3.20×10^{-4}	3.16×10^{-4}
6	1.68×10^{-3}	1.73×10^{-3}
7	1.51×10^{-3}	1.84×10^{-3}
8	1.01×10^{-3}	1.13×10^{-3}
9	2.77×10^{-3}	2.71×10^{-3}
10	1.32×10^{-4}	1.33×10^{-4}
11	1.06×10^{-3}	1.15×10^{-3}
12	1.76×10^{-3}	1.44×10^{-3}
13	6.33×10^{-4}	6.31×10^{-4}
14	1.74×10^{-3}	1.97×10^{-3}
15	4.69×10^{-4}	4.47×10^{-4}
16	1.40×10^{-3}	1.53×10^{-3}
17	8.40×10^{-4}	1.14×10^{-3}
18	5.17×10^{-4}	5.28×10^{-4}
19	1.80×10^{-3}	2.07×10^{-3}
20	2.24×10^{-4}	2.13×10^{-4}
21	3.32×10^{-4}	3.44×10^{-4}
22	6.00×10^{-4}	7.86×10^{-4}
23	1.00×10^{-3}	1.16×10^{-3}
Average	1.48×10^{-3}	1.60×10^{-3}
SD	1.43×10^{-3}	1.53×10^{-3}
P value	0.78	

In addition to comparing the K_s values, the heads for the conventional and automated methods have been compared, and they were similar for the two methods (Fig. 2B–4B). The lines fitted to the three sample soils yielded nearly equal R^2 values (R^2 values ≈ 1) for the two methods (Fig. 2B–4B). This is further evidence that the two methods yielded similar results.

Since specific soil type was not the objective of this study, K_s values for all soils were combined for further

Table 3. Hydraulic conductivity, averaged across time, for 11 silty clay loam soil samples using the conventional and automated methods.

	Silty clay loam	
Core	**Automated**	**Conventional**
	cm s^{-1}	
1	1.34×10^{-4}	1.30×10^{-4}
2	4.39×10^{-5}	5.23×10^{-5}
3	2.45×10^{-5}	2.11×10^{-5}
4	2.81×10^{-5}	2.69×10^{-5}
5	8.41×10^{-5}	7.63×10^{-5}
6	1.99×10^{-4}	1.66×10^{-4}
7	3.83×10^{-5}	4.64×10^{-5}
8	1.67×10^{-5}	1.56×10^{-5}
9	2.42×10^{-5}	2.86×10^{-5}
10	9.30×10^{-5}	9.11×10^{-5}
11	5.14×10^{-5}	5.67×10^{-5}
Average	6.70×10^{-5}	6.41×10^{-5}
SD	5.67×10^{-5}	4.81×10^{-5}
P value	0.92	

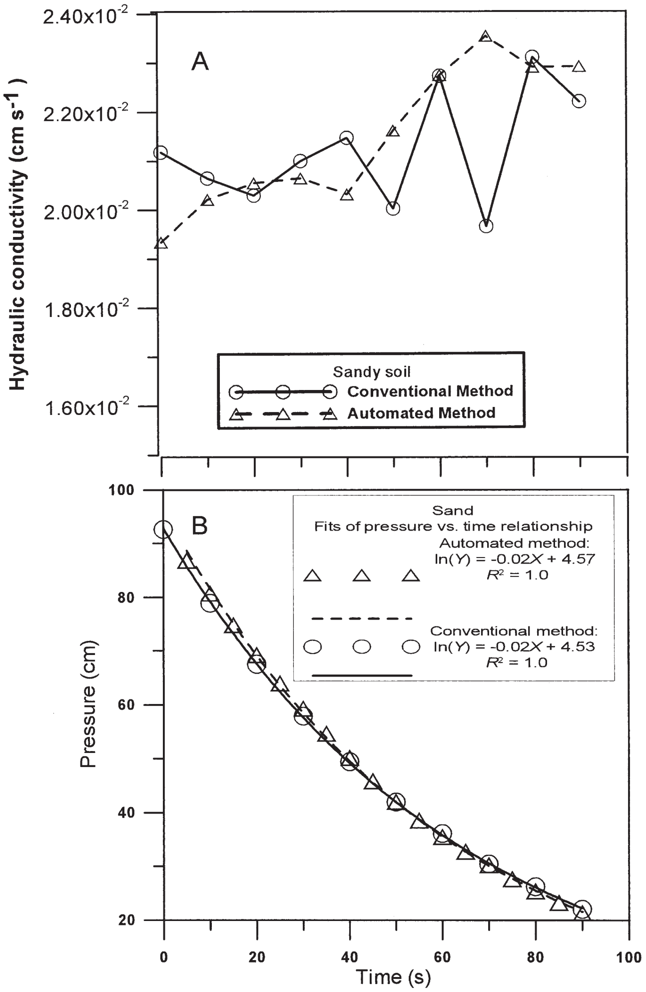

Fig. 2. (A) Hydraulic conductivity of saturated soil as a function of time for a sandy soil core obtained via conventional and automated falling head permeameter methods. (B) Pressure of falling head as a function of time for a sand sample.

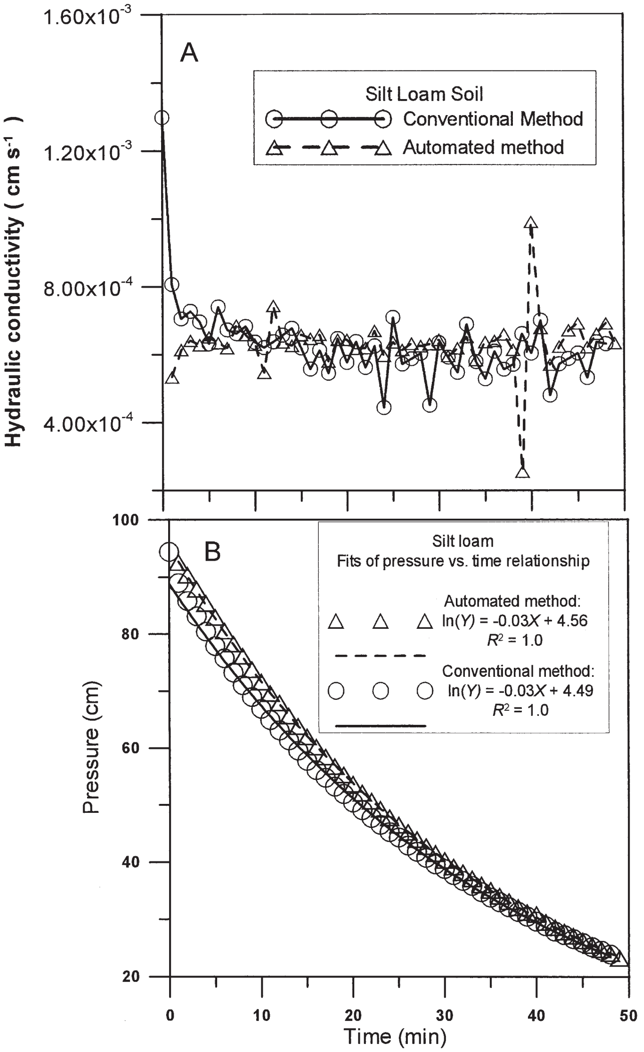

Fig. 3. (A) Hydraulic conductivity of saturated soil as a function of time for a silt loam soil core obtained via conventional and automated falling head permeameter methods. (B) Pressure of falling head as a function of time for a silt loam sample.

statistical analyses. A *P* value of 0.41, at the 95% level, was obtained from the paired *t* test comparison of the conventional and automated methods for the average K_s values for all 64 cores. Given this *P* value, we conclude that there is no significant difference between the two methods. The proposed automation of this method will greatly increase the number of samples that can be processed at a given time. With the system described in this paper, six samples can be measured without the need for constant human monitoring. However, it should be noted that the total number of samples that can be analyzed is not limited to six.

Limitations and problems observed while performing measurements included (i) the o-ring fitting inside the base of the permeameter may become worn during extended use, causing a loose fit between the soil cylinder and permeameter, resulting in leaks. (ii) Forcing the permeameter over the soil cylinder may cause disturbance to the soil or leakage in the permeameter. However, if the cylinder and o-ring are wet, o-ring damage can be reduced and the permeameter can easily be installed. (iii) The force of the water from the initial filling of the standpipe can cause a disturbance to the soil sample. This can be avoided by directing the water along the sides of the standpipe with the use of flexible tubing or a funnel. (iv) Because of the slow rate of conductivity through dense clays, datalogger sampling rates need not be set at small time steps (i.e., 10 s). Larger datalogging time steps will allow for sufficient changes in the hydraulic head, thus permitting calculation of K_s values > 0.

Conclusions

With the proposed automated falling head permeameter, laboratory K_s measurements can be measured rapidly and efficiently. One can measure a larger number of samples using this technique. However, it should be noted that samples within a given texture classification should be analyzed together. Short datalogger execution intervals are necessary for coarse materials as opposed to intermediate to long execution intervals for finer (silt and clay) materials. This technique also has an advantage over the conventional (manual) method in that it offers less chance for error in reading falling head

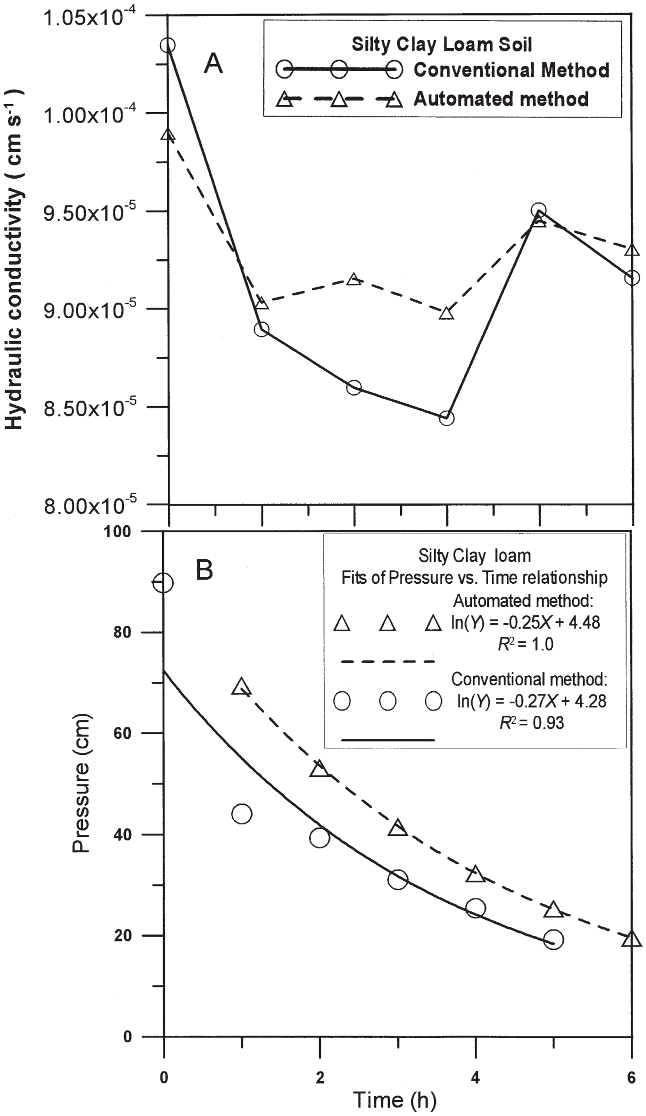

Fig. 4. (A) Hydraulic conductivity of saturated soil as a function of time for a silty clay loam soil core obtained via conventional and automated falling head permeameter methods. (B) Pressure of falling head as a function of time for a silty clay loam sample.

values for estimating the hydraulic gradient, assuming pressure transducers are properly calibrated and tested for drift and zero shift frequently.

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