Improving Hydraulic Conductivity Determination of Aquifers by High Precision Pressure Driven Pumping System

M. H. Dahanayake, R. Weerasooriya

Abstract: Current methods to measure hydraulic conductivity use gravitational forces for the pumping of water to the permeameter, and shows limitations such as bulkiness, increased experimental time, and inability to apply required experimental conditions. Therefore, a novel method is proposed which uses LC 8A preparative liquid chromatography pumping system to inject water to the apparatus, thus, hydraulic conductivity can be obtained with precision. A silty sand sample collected from Netiyagama, Anuradhapura was utilized to measure hydraulic conductivity, and a value of 2.96 x 10^{-3} cm/s was obtained with the conventional falling-head method. Whereas with the improved method, hydraulic conductivity changed with the change of pressure. The highest conductivity value (7.84 x 10^{-3} cm/s) was obtained with a higher flow rate of 150 ml/min, and at a high pressure of 300 kgf/cm^2. The lowest conductivity value of 1.57 x 10^{-5} cm/s was obtained when the flow rate (0.1 ml/min) and the pressure (10 kgf/cm^2) were at their lowest. In conclusion, the proposed method shows more promising hydraulic conductivity values, compared to the conventional method, in addition to easy handling, decreased experimental time, capability of automation, and simplified design.

Keywords: flow rate, hydraulic conductivity, permeameter, pressure pump

1. Introduction

Soil hydraulic conductivity or permeability is known as the capability of soil to transmit water under saturated or nearly-saturated conditions. Hydraulic conductivity values are used by hydrogeologists and other scientists to estimate soil health, the water flow through soil at different locations, irrigation rates, erosion, nutrient leaching, etc. (Chapuis, 2012). In practical sense, the conductivity values are essential for the development of safe and cost-effective lands to be used for urban development. The design and construction of building and road foundations, on-site sewage wastewater treatment systems, storm water infiltration facilities, etc. require careful consideration of hydraulic conductivity values (Jarvis et al., 2013). These values are crucial for the design of artificial wetlands and for calculating the speed at which liquid contaminants are transported from

M.H. Dahanayake, Research Assistant, NIFS
Email: madushani.da@nifc.ac.lk
ORCID ID: https://orcid.org/0000-0003-1354-4683
***R. Weerasooriya**, Research Professor, NIFS; Joint Research and Demonstration Center for Water Technology (JRDC)*
Email: rohan.we@nifc.ac.lk
ORCID ID: https://orcid.org/0000-0002-0509-5307

waste disposal sites and leaking storage tanks. Values for hydraulic conductivity are also essential when designing irrigation systems and drainage for agricultural lands. Moreover, one of the most important soil properties in geotechnical engineering projects is hydraulic conductivity (Fredlund & Houston, 2009). These conductivities depend on different factors such as soil particle size, texture, roughness, shape, tortuosity, and degree of interconnection of water-conducting pores. Among these, soil structure and pore structure have a significant influence on water transmission through soil (Suleiman & Ritchie, 2001).

Darcy's law is used to determine the porous soil medium's hydraulic conductivity (Lu et al., 2006). Darcy's law is a constitutive equation that was developed based on experimental research on the flow of water through sand beds. It states that groundwater flows through a porous medium from the upper side toward the bottom side of a hydraulic head at a rate that is proportional to the hydraulic gradient and hydraulic conductivity. It is known as saturated hydraulic conductivity when it is present in saturated environments, such as below a water table (Chapuis, 2012). Despite the fact that Darcy's law was initially created to describe saturated flow, its principles can also be used to explain how water moves through partially saturated soils above the water table.

There are strategies for measuring soil hydraulic conductivity. Constant head and falling head methods are two of the most popular techniques used in laboratories to measure hydraulic conductivity (van der Kamp, 2001). The constant head permeameter method maintains a specific pressure head by continuously supplying fluid to a porous medium. The following relation specifies the hydraulic conductivity (K).

$$K = LQ/H\pi R^2 \;\ldots\ldots\; (1)$$

Where;
Q = volume flow rate (m^3/s)
L = length of the trajectory (m)
R = radius of the trajectory (m)
H = hydrostatic pressure or head (N/m^2)

A similar relationship is used by the falling head permeameter for the discharge, Q. The standpipe's water level is falling at the following rate:

$$Q = Av = \pi r^2 (dH/dL) \;\ldots\ldots\; (2)$$

Where;
A = cross sectional area of the standpipe (m^2)
v = falling head velocity (m/s)
r = radius of the standpipe (m)

And Darcy's Law can be applied to the soil column as:

$$Q = \pi R^2 K\,(H/L) \;\ldots\ldots\; (3)$$

The hydraulic conductivity for a falling head permeameter is represented by the following relationship after equating both of the above equations and integrating:

$$K = (\pi r^2 L/\pi R^2 t)\,\ln(H_1/H_2) \;\ldots\ldots\; (4)$$

Where;
H_1/H_2 = head ratio of initial to final head at a time t(s)

Due to the high permeability of coarse sands and gravels, the constant head permeameter is best suited for determining the hydraulic conductivity of these materials, whereas the falling head permeameter is more appropriate for fine silt and clay-like soils (Wanielista et al., 1997). Both the constant and falling head methods use a test chamber called a flexible wall permeameter, which contains a porous medium. The American Society for Testing and Materials has established stringent guidelines for laboratory practices when obtaining and analyzing a sample of porous material (ASTM, 2017). The laboratory techniques discussed are standard approaches for calculating permeability from field-collected small soil samples.

The constant head permeameter method maintains a specific pressure head by continuously supplying fluid to a porous soil medium. The inflow of water percolates through the porous sample from below and exits through the duct (valve) on the lid. Other method uses the falling head permeameter, which passes water through the sample and out the duct while using a time-dependent hydrostatic pressure profile in the standpipe. These methods show limitations such as bulkiness, higher time consumption, inability to apply required experimental conditions, relatively complex set-up, manual pumping of water to the permeameter, and inaccuracy in obtained values.

Accordingly, the present invention has been made to measure hydraulic conductivity with improved efficiency keeping in mind the previously stated limitations of conventional methods. In order to avoid these limitations, a high pressure LC 8A preparative liquid chromatography pump is attached to the permeameter and the pumping of water to the apparatus is automated. This avoids potential human error and eliminates constant measuring and adjusting of flow rate of water. Moreover, it offers user-friendly single point control. The setup is relatively easy to handle as it excludes the attachment of standpipe or manometer. Moreover, simultaneous water transmission and retention can be achieved via this improved setup. Also, there is capacity to change water temperatures and water types (such as seawater). Additionally, both saturated and unsaturated flow parameters can be measured on the same soil column.

2. Methodology

A silty sand sample collected from Netiyagama, Anuradhapura was utilized to measure hydraulic conductivity. Initially, the sand sample was packed tightly in the soil core of permeameter. The mobile phase outlet of LC 8A preparative pump was attached to the water inlet of permeameter by a connection tube. Water was pumped from the reservoir through a suction filter to the soil core at pressures 10, 100, 150, 200, and 300 kgf/cm^2. All the air bubbles trapped inside the soil were removed from the water outlet to make the soil saturated. Once the soil reached saturation, the values for flow rate were taken. Each test was performed three times and the average values were taken for hydraulic conductivity calculations.

3. Results and discussion

A hydraulic confinement and measuring system for determining hydraulic conductivity of various aquifers is developed. The main feature of the present invention is the provision of LC 8A preparative liquid chromatography pump unit. The mobile phase outlet of the pressure pump and the permeameter are being interconnected via a flexible tube to inject water to the bottom water inlet of permeameter consisting a cylindrical, pressurized soil core, instead of using a standpipe or manometer.

To utilize the apparatus of the present invention, the soil sample to be tested must be compacted inside the chamber of the permeameter. Compaction is achieved by placing a porous metal plate at the bottom of the chamber and loading the soil sample on the plate pressing down layer wise using a one hundred gram weight. After compaction, the top surface of the sample is smoothed off evenly so that the surface area can be accurately calculated. When compaction has been completed, another porous plate is kept on top of the soil sample and the lid is attached to the open top of the chamber to seal the sample. A void or spacing is located between the top of the sample and the bottom surface of the lid.

LC 8A preparative pump unit shall be prepared next. A water reservoir is connected to the inlet of the machine by a flexible tube and another flexible tube is connected to the mobile phase outlet of the machine to remove water. Once all the settings, namely minimum pressure, maximum pressure, and duration, are entered to the machine and tubes are attached, it is ready for pumping of fluid. Prior to attaching the permeameter to the machine, all the trapped air inside the machine shall be removed. For this purpose, water is pumped from the reservoir via the machine and removed through the mobile phase outlet. Once all the trapped air are eliminated, a continuous flow of fluid is obtained. At this stage, permeameter may be attached to the preparative pump.

The mobile phase outlet of LC 8A preparative pump is attached to the water inlet of permeameter by a flexible connection tube. Water is pumped from the water reservoir of the LC pump unit through a suction filter to the soil core of permeameter, once the settings of the pump unit are fixed. The trapped air bubbles inside the soil core are removed prior to the saturation point. At a certain time, hydraulic head difference between upper and bottom levels of the core and flow rate per unit area for a unit time (Darcy flux) become constant. At this point, the sample has attained a saturated level. It is assumed that the flow rate of fluid through the pump equals to the flow rate of fluid through the soil sample after saturation. Therefore, the flow rate can be directly taken from the LC 8A preparative pump unit and the hydraulic conductivity of soil can be calculated as a one-step process using the equation 5.

$$K = Q/(2\pi rh + 2\pi r^2) \;\ldots\ldots\; (5)$$

Where;
K = soil hydraulic conductivity (cm/s)
Q = flow rate reading on LC 8A preparative pump (cm^3/s)
r = radius of the inner surface of cylindrical chamber of permeameter (cm)
h = height of the cylindrical chamber (cm)

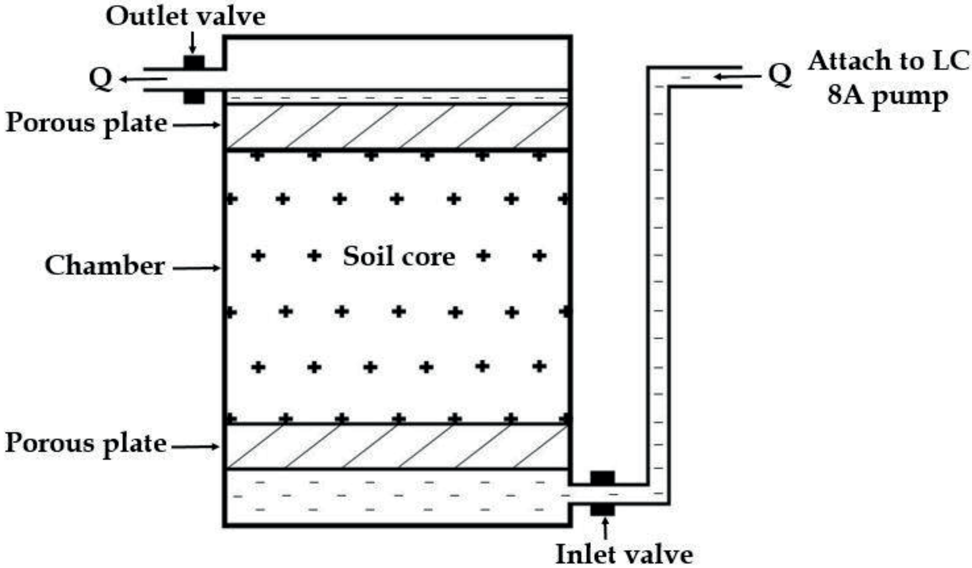

Figure 1 - Attachment scheme of LC 8A preparative pump unit to the permeameter in the invented method

The hydraulic conductivity varied with the change of applied pressure, as shown in table 1, when utilizing the improved method. It is noted that the flow rate of water has increased with the increase of applied pressure by the pump. As a result, hydraulic conductivity values have also been increased, as it is proportional to the flow rate. Thus, the highest conductivity of 7.84 x 10^{-3} cm/s was obtained when the applied pressure was at its highest and wise versa.

To validate the results, the conventional falling head method was carried out and a hydraulic conductivity of 2.96 x 10^{-3} cm/s was obtained for the silty sand sample, which was within the range of conductivity values attained from the improved method. The above conductivity value was slightly similar to the value obtained when a maximum pressure of 100 kgf/cm^2 had been applied using the LC 8A pump. Thus, it can be assumed that this pressure range can be similar to the pressure produced from the gravitational forces during the falling head test. Moreover, the time taken for a certain volume of water to flow out of the outlet of permeameter when using the LC 8A pump was assessed, and the flow rates were calculated to further validate the results of the developed method.

Table 1 - Hydraulic conductivity values and flow rates with applied pressures, obtained from LC 8A preparative pump

Applied pressure (kgf/cm^2)	Flow rate (cm^3/min)	Hydraulic conductivity (cm/s)
10	0.1	1.57 x 10^{-5}
50	2.0	3.14 x 10^{-4}
80	10.0	1.57 x 10^{-3}
100	18.0	2.82 x 10^{-3}
150	28.0	4.40 x 10^{-3}
200	45.0	7.06 x 10^{-3}
300	50.0	7.84 x 10^{-3}

The invented system is capable of performing conductivity measurements with any type of aquifer, wherein it has the capability to apply desired flow rates and pressures and obtain respective hydraulic conductivity values. Moreover, it shows more promising hydraulic conductivity values, compared to conventional methods, in addition to easy handling, decreased experimental time, capability of automation, and enhanced efficiency.

4. Conclusions

The present invention has the effect of directly measuring the saturated hydraulic conductivity of the soil by taking the flow rate produced by the LC 8A pressure driven pumping system. Water is pumped from the water reservoir of the LC pump unit through a suction filter to the soil core of permeameter. Further, the soil core and connecting pipe are configured causing water around the soil core to flow from the bottom level towards the upper level within the core so that the hydraulic conductivity of soil is efficiently calculated by means of hydraulic head difference between the upper and bottom levels of the core. In addition, the attachment of a LC 8A preparative pump enhances the efficiency and easy operation of the apparatus accompanied by streamlined design, decreased time consumption, ease of installation and maintainability, and the need for little to no training to successfully operate the innovation.

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