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Experimental determination of hydraulic conductivity at unsaturated soil column

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Abstract

Hydraulic Conductivity (K) is an important hydraulic parameter as it affects the environment by controlling infiltration, irrigation rate, and consequently the water movement through the ground. In order to determine Hydraulic Conductivity in a soil column during unsaturated flow, experiments were performed in the laboratory. A sandy (S) soil sample of known Hydraulic Conductivity at saturation (K_S) was placed uniformly in a transparent column. Using a pump, water was applied at the surface of the soil column in certain supplies (Q_i), while soil moisture (θ) was measured using TDR probes. At the same time, soil pore pressure (h) was measured using pressure transducers. The cumulative volume of the outgoing water (V) of the column was measured. Experimental data were fitted by Van Genuhten's Hydraulic Conductivity model. The results of the above experimental procedure constitute useful tools for the simulation of water movement in unsaturated soils and can be the outset for further research.

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Keywords: hydraulic conductivity; unsaturated flow; soil moisture; soil pore pressure; soil column

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1. Introduction

The rational use in agricultural crops, depends on the knowledge of the phenomenon which determines the movement of water in soil. The ability of soils to retain and carry water is regulated by hydraulic properties one of which is the hydraulic conductivity in relation to soil moisture K(θ) or in relation to water pressure K(h).

Generally, the movement of water in soil is three-dimensional, but in most cases can be considered as two-dimensional because of the axial symmetry and in many cases can be considered as one-dimensional. The vertical movement of water in soil is found in irrigation systems and in the enrichment of aquifers.

The study of the movement of water in unsaturated soil launched in 1907 by Buckingham who tried to give a detailed analysis of the unsaturated flow as it mentioned by Swartzendruber, [18]. Richards [12] extended the law of Darcy and unsaturated flow. But Childs [5] started a systematic research of water movement in the soil and gave a complete description of the physical phenomena governing the movement of water in soil.

Many scientists who dealt with the systematic study of unsaturated flow are Childs and Collis-George [6], Vachaud [20], Philip [11], Swartzendruber [18], Parlange [9], Sakellariou-Makrantonaki et al. [13].

A significant prediction model of Hydraulic Conductivity in unsaturated condition of the soil is van Genuchten's model:

$$K(\theta) = K_s \Theta^{\frac{1}{2}} \left[1 - \left(1 - \Theta^{1/m}\right)^m\right]^2 \tag{1}$$

where K is the hydraulic conductivity, K_s is the hydraulic conductivity at saturation, m = 1 – 1 / n (0<m<1; n>1) is a parameter which is related to curve deformation and *Θ* is the soil moisture, which is defined as:

$$\Theta = \frac{\theta-\theta_r}{\theta_s-\theta_r} = \frac{1}{((1+(ah)^n)^m} \tag{2}$$

where θ_r is the residual moisture, θ_s is the soil moisture at saturation, h is the soil pore pressure and a is an adjustment parameter.

The development of computer science contributed to a more detailed approach to the movement of water in unsaturated zone. At the same time, computers helped researchers in the development and presentation of mathematical models that describe the movement of water in unsaturated zone with the ability of automatic data recording. There are many researches in the international literature and indicatively examples are Sakellariou-Makrantonaki and Hajiyiannakis [14], Sakellariou-Makrantonaki [15], Vogel et al. [21], Angelaki et al. [1, 2], Or and Tuller [8], Mertens et al. [7], Šimůnek et al. [17], Vogel and Ippisch [22], Touma [19], Carrick et al. [4], Pfletschinger et al. [10], Shein et al. [16].

2. Methodology

Granulometric analysis and Hydraulic Conductivity at saturation (Ks) of the soil sample, were measured at the laboratory, using the constant head method (ASTM, [3]). The method operates in accordance to the direct application of Darcy's law to a soil liquid configuration representing a one-dimensional, steady flow of a percolating liquid through a saturated column of soil from a uniform cross-sectional area. This procedure allows water to move through the soil under a steady state head condition while the quantity (volume) of water flowing through the soil specimen is measured over a period of time. By knowing the quantity of water measured, length of specimen, cross-sectional area of the specimen, time required for the quantity of water to be discharged and constant head difference, the Hydraulic Conductivity at saturation can be calculated:

$$K_s = \frac{QL}{A\Delta H} = \frac{VL}{At\Delta H} \tag{3}$$

where A is the cross-sectional area of the specimen, V is the volume of water, L is the length of the specimen, $\Delta H = H_1 - H_2$ is the constant-head difference and t is the time.

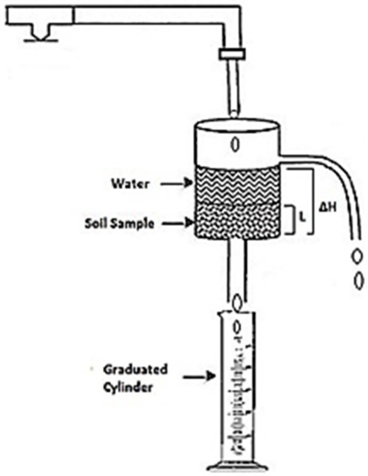

Fig. 1. Schematic diagram for the measurement of the saturated Hydraulic Conductivity by constant-head method.

The soil sample was placed uniformly in a transparent column of 6 cm inner diameter and 55 cm length. The height of the soil sample was 39.5 cm. Four supplies (Table 1) were applied at the surface of the soil column using a pump, the values of which were lower than Hydraulic Conductivity at saturation (K_s). Soil moisture (θ) was measured using TDR probes at certain locations. TDR is a method for measuring soil moisture content using electromagnetic waves. Each measuring circle lasted 2 minutes and the total number of circles for each supply (Q_i) was about 50. Final value of soil moisture was θ_s (which corresponds to value of K_s) was measured separately at the laboratory using the gravimetric method ($\theta_s = 0.26$). At the same time, soil pore pressure (h) was measured using a ceramic cap connected to a pressure transducer which sensitivity was 4.659 mV/V (given by the manufacturer) (Fig. 2). The pressure transducer was calibrated using a transparent column full of water and a Mariotte bottle. The equation of calibration was:

$$y = 25.086x - 19.348 \tag{4}$$

where y is pressure in cm and x is voltage in mV (Fig. 3). Also, the cumulative volume of the outgoing water (V) of the column was measured. Using experimental data, graphs of Hydraulic Conductivity (K) in relation to soil moisture (θ), soil pore pressure (h) and cumulative volumes of outgoing water (V) in relation to time (t) were figured. Experimental data were fitted by Van Genuhten's Hydraulic Conductivity model.

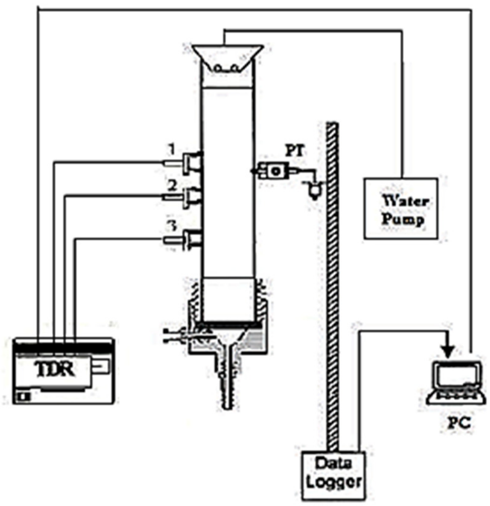

Fig. 2. Schematic diagram of the experimental setting.

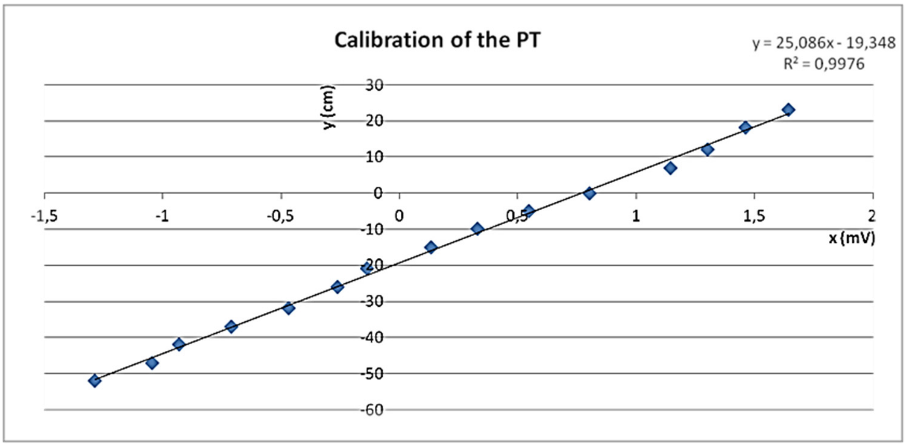

Fig. 3. Calibration curve of the pressure transducer.

3. Results

Soil sample was characterized as Sandy (S), due to granulometric analysis, while the value of Hydraulic Conductivity at saturation (Ks) was Ks=93 cm/h and flow rate at saturation was Qs=43.8 cm^3/min.

The distance of the TDR probes from the soil surface are shown in Table 2. The ceramic cap which was connected to the pressure transducer was placed 6.5 cm below soil surface.

Table 1. Water supplies that were applied on soil surface.

a/a	Q (cm/h)
1	2.8
2	5.3
3	18

4	22

Table 2. Distance of TDR probes from soil surface.

a/a	Z (cm)
1	3.5
2	13.5
3	23.5

Using the values of supplies (Qi), values of Hydraulic Conductivity (K) of unsaturated soil were calculated. The experimental points of Hydraulic Conductivity (K) versus Soil Moisture (θ) (TDR data), are shown in Fig. 4.

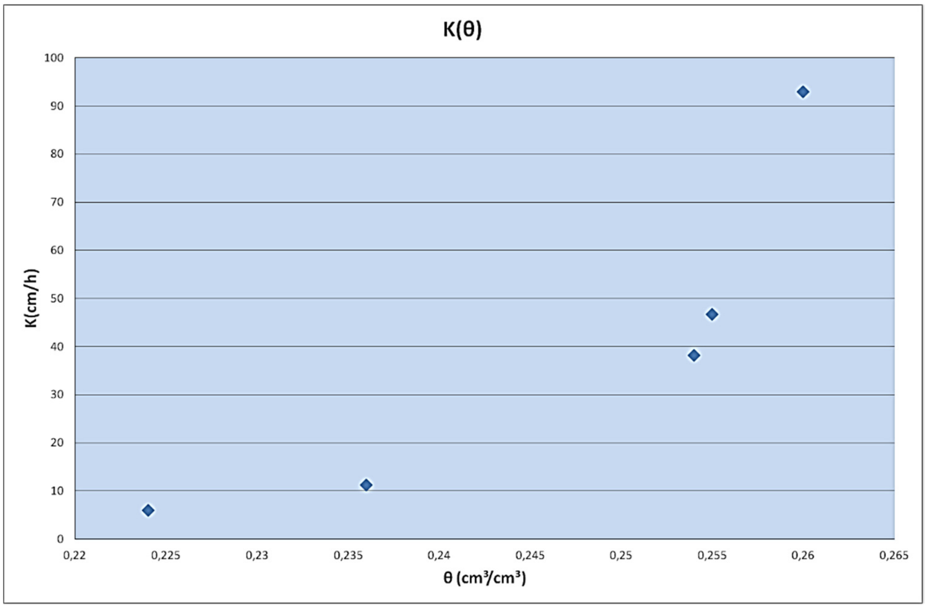

Fig. 4. Hydraulic Conductivity (K) in unsaturated soil in relation to soil moisture (θ).

Experimental points of Hydraulic conductivity at unsaturated condition in relation to absolute values of soil pore pressure (h) are shown in Fig. 5.

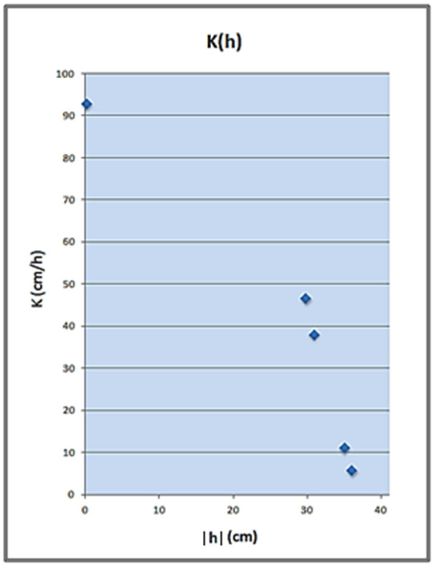

Fig. 5. Hydraulic Conductivity (K) versus soil pore pressure (h).

Cumulative volumes of outgoing water versus time for the four different water supplies applied on the soil surface are shown in Fig. 6.

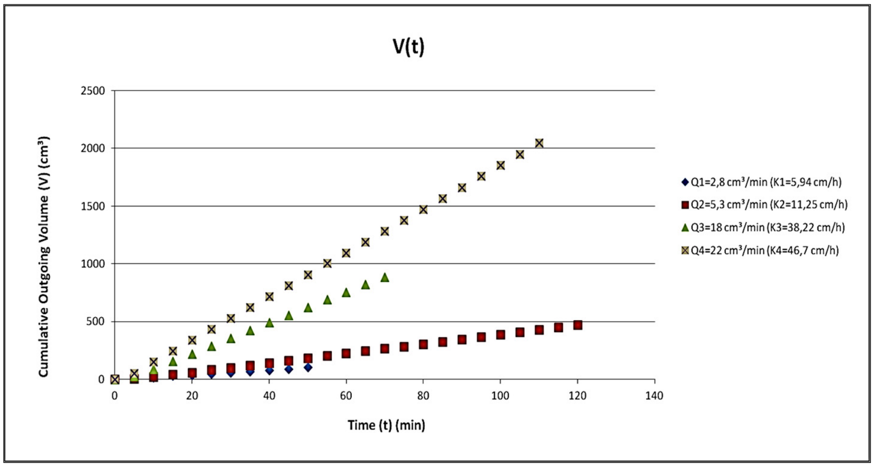

Fig. 6. Cumulative outgoing volumes (V) versus time (t).

Equation (1) (van Genuchten's prediction model) was used in order to approximate experimental points of K(θ). Using experimental data of soil moisture (θ) and soil pore pressure (h) into Equation (2), parameter n was calculated (n=19.61521). In Fig. 7 it can be seen that van Genuchten's model approximates very well the experimental points of K(θ) (R-squared=0,9974).

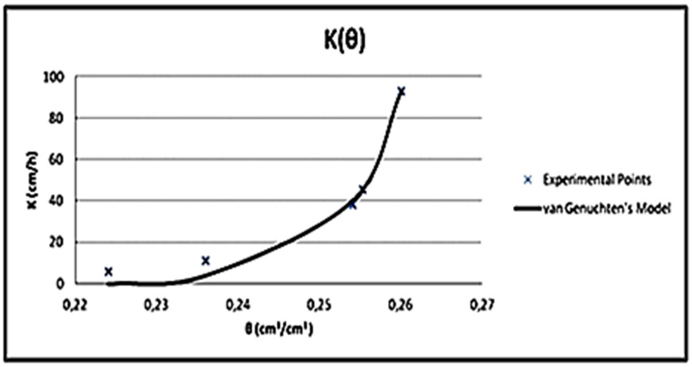

Fig. 7. Approximation of experimental points with van Genuchten's model.

4. Conclusions

In this study, laboratory experiments were carried out at Agricultural Hydraulics Laboratory of the Department of Agriculture, Crop Production and Rural Environment of University of Thessaly. Particularly, a Sandy (S) soil sample was placed in a transparent column and four different water supplies were applied on the surface of the soil column, in order to collect experimental data of soil moisture and soil pore pressure, in relation to Hydraulic Conductivity at unsaturated condition. Also, outgoing cumulative water volumes versus time were measured. Van Genuchten's model fitted with a good approximation the experimental points of K(θ).

Experimental data are a valuable source that can be used for further research of more hydraulic parameters of soil at unsaturated condition and constitute useful tools for the simulation of water movement in unsaturated soils. The results of the above experimental procedure are useful for irrigation and drainage research field.

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