



Estimating saturated and unsaturated hydraulic conductivity and sorptivity coefficient in transient state in sloping lands

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Abstract

Double ring and tension infiltrometer are simple and suitable instruments for determining soil hydraulic conductivity and soil sorptivity coefficient. The effect of land slope on soil properties, such as saturated and unsaturated hydraulic conductivity and soil sorptivity coefficient, has been reported by various researchers. The aim of this study was to estimate soil hydraulic conductivity and soil sorptivity coefficient values in lands with different slope gradients, under transient flow conditions. Field experiments were conducted in a loamy soil with different slope gradients in Gonbad Research Station, Hamadan, Iran. Soil surface slope gradients 0 (level), 10, 20, 30 and 40 degrees were selected in this study. For each slope gradient, water infiltration experiments were carried out using a double ring and a tension infiltrometer at tensions of 0, 6, 9 and 15 cm in three replications. Totally 60 water infiltration experiments were carried out. In transient state, Philip's two-term infiltration equation was applied to determine soil sorptivity coefficient and soil hydraulic conductivity using cumulative infiltration data obtained from the double ring and tension infiltrometer. In this state, the sorptivity coefficient and the hydraulic conductivity for different land slopes and water pressure heads were calculated from Philip's two-term infiltration equation, which can be obtained by fitting the Philip's equation to cumulative infiltration data. Results indicated that both the sorptivity coefficient and the hydraulic conductivity values were decreased with increase in tension values. Also the sorptivity coefficient value was increased and the hydraulic conductivity value was decreased with increase in slope gradient. The higher value for decreasing rate of hydraulic conductivity was obtained in lower tensions. With increase of slope gradient from 0 to 40 degrees, decreasing rate of hydraulic conductivity in 0 tension was 3.7 times higher than that in 15 cm tension. With increase in slope gradient the higher value for increasing rate of sorptivity coefficient was obtained in lower tensions.

Key words: Saturated and unsaturated hydraulic conductivity, sorptivity coefficient, double ring and tension infiltrometer, transient state.

Introduction

Hydraulic conductivity is one of the most important hydraulic properties, which affect water flow and solute transport in saturated and unsaturated soils. Also, sorptivity is the basic hydraulic property relating to the square root of time in Philip two-term infiltration equation. In many parts of the world, most of lands are sloping. Most of precipitation and snowmelt water take place in sloping lands. Several researchers have reported that land slope influences soil properties such as moisture distribution, infiltration rate, cumulative infiltration, sorptivity coefficient and saturated and unsaturated hydraulic conductivity^{3, 13, 14, 23}. Few measurement techniques and instruments exist for determining soil hydraulic properties and sorptivity coefficient in sloping lands^{3, 18}. These include the use of excavated trenches⁷, excavated trenches along the contour line¹⁰, tracers, piezometers, tensiometers and suction lysimeters¹⁶ and hillslope infiltrometer⁹. Under field conditions, these methods are time consuming, laborious and destructive, also hillslope infiltrometer instrument is not produced in commercial scale³. Double ring infiltrometer⁴ and tension infiltrometer¹¹ are simple, fast, convenient and useful instruments for determining soil hydraulic properties based on *in situ* infiltration experiments. Double ring infiltrometers have been widely used for estimation of saturated hydraulic conductivity under ponding conditions⁴.

Also, tension infiltrometers have been proven useful for characterizing unsaturated hydraulic conductivity^{2, 15, 21}, sorptivity coefficient²³, mobile and immobile water content¹ and water conducting porosity^{6, 20}. Water infiltration from a tension infiltrometer placed at a sloping landscape can be simulated with various disk diameters, water pressures applied at the soil surface and sloping degrees. The saturated and unsaturated hydraulic conductivity in steady and transient states can be estimated using cumulative infiltration, which is measured by double ring and tension infiltrometer. In transient flow, the amount of water flowing through the voids of soil changes and the infiltration rate reduces with time. In this state, Philip's two-term infiltration equation can be used to determine the sorptivity coefficient and the hydraulic conductivity by taking advantage of cumulative infiltration data obtained from double ring and tension infiltrometer. This equation has been defined as¹²

$$I = C_1 t^{\frac{1}{2}} + C_2 t \quad (1)$$

where I is the cumulative infiltration [L], C_1 [$L T^{-\frac{1}{2}}$] and C_2 [LT^{-1}] are empirical parameters and t is the time [T]. C_1 and C_2 can be related to sorptivity coefficient and soil hydraulic conductivity²³:

$$C_1(h) = A_1 S(h) \quad (2)$$

$$C_2(h) = A_2 K(h) \quad (3)$$

where A_1 and A_2 is a dimensionless coefficient and h is the tension value of the infiltrometer used during the infiltration experiment ($h \leq 0$). By estimating the parameters A_1 and A_2 the sorptivity coefficient and the hydraulic conductivity can be determined in different slope gradients and water pressure heads. In transient state, determination of the sorptivity coefficient and the saturated and unsaturated hydraulic conductivity requires soil hydraulic functions such as soil retention function ($\theta(h)$) and hydraulic conductivity function ($K(h)$). The hydraulic characteristics of the soil under consideration showed better fitness with van Genuchten's hydraulic functions¹⁷. Van Genuchten's retention function is described as

$$S_e(h) = \frac{\theta - \theta_r}{\theta_s - \theta_r} = [1 + (\alpha h)^n]^{-m} \quad (4)$$

where

$$m = 1 - \frac{1}{n}, \quad n > 1 \quad (5)$$

and the corresponding hydraulic conductivity function reads

$$K(h) = K_{sat} s_e^{0.5} [1 - (1 - s_e^{\frac{1}{m}})^m]^2 \quad (6)$$

where θ_r and θ_s are the residual and saturated water contents, respectively, n and α [L^{-1}] are parameters defining the shape of $S_e(h)$ and $K(h)$ curve, and K_{sat} is the saturated hydraulic conductivity [LT^{-1}]. The sorptivity and hydraulic conductivity coefficients (C_1 and C_2) are obtained by fitting the cumulative infiltration data with Philip's infiltration equation (Eq.(1)). Then sorptivity coefficient and soil hydraulic conductivity can be determined by

$$S(h) = C_1/A_1 \quad (7)$$

$$K(h) = C_2/A_2 \quad (8)$$

The dimensionless coefficients A_1 and A_2 change slightly during infiltration experiment, which can be neglected and assumed constant. Zhang²³ established following empirical relationships for A_1 and A_2 as function of soil retention parameters, infiltrometer parameters and initial water content, which are compatible with Eq.(4) and (6):

$$A_1 = \frac{1.4 b^{0.5} (\theta - \theta_i)^{0.25} \exp [3(n-1.9)\alpha h]}{\alpha r_0^{0.15}} \quad (9)$$

$$A_2 = \frac{11.65(n^{0.4} - 1) \exp [2.92(n-1.9)\alpha h]}{(\alpha r_0)^{0.94}}, \quad n \geq 1.9 \quad (10)$$

$$A_2 = \frac{11.65(n^{0.4} - 1) \exp [7.5(n-1.9)\alpha h]}{(\alpha r_0)^{0.94}}, \quad n < 1.9 \quad (11)$$

where n and α are the retention parameters, h [L] is the pressure head of the infiltrometer in each experiment ($h \leq 0$), r_0 is the radius of the infiltrometer [L], θ is the water content at h , and θ_i is the initial water content, and b is a parameter, has been reported between $\frac{1}{2}$ and $\frac{\pi}{4}$. In this study we used the representative value $b = 0.55$ ^{15,19}.

Materials and Methods

This study was conducted at Gonbad research station, Hamadan, Iran (48°42.14'N lat., 34°41.74'W long. and 2170 m elev.). According to the laboratory analysis, soil texture in the experimental area is loamy, based on USDA soil textural triangle. Some of physical properties such as particle density, bulk density, porosity and sand, silt and clay percentage of soil are listed in Table 1. Five various soil surface slope gradients including 0-, 10-, 20-, 30- and 40-degree slopes were selected in the area. For each slope gradient, water infiltration experiments were carried out by a double ring and a tension infiltrometer at tensions 0, 6, 9 and 15 cm of water in three replications. Totally 60 water infiltration experiments were carried out in five different surface slopes, four tensions and three replications ($5 \times 4 \times 3 = 60$). A soil profile with 1.5 m length, 1.5m width and 2 m depth was excavated. Soil layer was homogenous and abrupt changes in soil texture and soil layer were not observed within 2 m of the soil profile. When the amount of water entered into the soil did not change with time for three consecutive measurements taken at 5-minute intervals, steady state flow was assumed and the corresponding infiltration rate was calculated based on the last three measurements. Generally, steady state flow was achieved within 30 to 60 min for the tension infiltrometer and within 60 to 120 min for the double ring infiltrometer. To estimate sorptivity and hydraulic conductivity in saturated condition, a double ring infiltrometer with inner and outer rings of 0.2 and 0.3 m in diameter, respectively, was used at a constant head²⁴. Steel rings were pushed into the soil concentrically to a depth of 0.05 m approximately with minimum soil disturbance. Then the inner cylinder and space between two cylinders were filled with water to 0.1 m water head. Water level falling in the inner cylinder during the experiment was recorded by pointer. Water level in the outer ring was maintained exactly at the same height as that in the inner ring. To estimate sorptivity and hydraulic conductivity in unsaturated condition, a tension infiltrometer with a 0.2 m diameter disk (soil measurement systems, Tuscon. Az) was used. At first the location of experiment was selected and then a thin layer (5×10^{-3} m) of moist fine sand was applied over the prepared surface at each measurement location in a circular area with a diameter equal to the diameter of infiltrometer disk. The hydraulic conductivity of testing sand must be more than that of the experimental soil. Applying the fine sand has two advantages as follows³: 1) the sand prevents tearing the nylon mesh attached to the infiltrometer disk; 2) this smoothes out any irregularities of the soil surface and ensures good contact between the soil surface and the infiltrometer membrane.

After preparation of the experiment location, tension infiltrometer instrument was regulated in given tension and was placed on it. The amount of infiltration into the soil was measured by recording the water level falling in the graded reservoir tower as a function of time. The sorptivity coefficient and the saturated and unsaturated hydraulic conductivity values were calculated by Matlab software.

Results and Discussion

To determine the soil physical properties in different slopes, for each slope three disturbed and three undisturbed samples (0.05 m in diameter and 0.05 m in height) were taken from areas next to the measurement locations. Table 1 gives the soil physical properties in different slopes. Figs 1 and 2 illustrate the cumulative infiltration versus time for different tensions in 0- and 40-degree slope gradients. For saturated condition ($h=0$) the cumulative infiltration data was obtained by a double ring infiltrometer instrument and for unsaturated conditions ($h=6, 9$ and 15 cm) by a tension infiltrometer instrument. Then the trend of sorptivity coefficient and hydraulic conductivity changes with slope or tension variations were determined. The residual soil water content at 33 and 1500 kP tensions were measured by a pressure plate instrument. Using values of the residual soil water content at these tensions, sand, silt and clay percentage and bulk density all as inputs, four parameters of van Genuchten soil hydraulic functions (residual soil water content $[\theta_r]$, saturated soil water content $[\theta_s]$ and empirical shape factors $[n]$, $[\alpha]$) were estimated by artificial neural network method. On the other hand, for different slope gradients and tensions, C_1 and C_2 values were obtained by fitting cumulative infiltration data with Philip's two-term infiltration equation using a maximum neighborhood method⁸. Then sorptivity coefficient and hydraulic conductivity values for different slope

gradients and tensions were determined by Equations (7) and (8), respectively²³. The trend of hydraulic conductivity and sorptivity coefficient changes with increase in applied tension at different slope gradients is illustrated in Figs 3 and 4, respectively.

Figs 1 and 2 show that for a given land slope, the cumulative infiltration, I , decreases with increasing capillary tension, h , for $h=0, 6, 9$ and 15 cm. It is also seen that for the same tension, the cumulative infiltration is smaller for greater land slope, indicating the inverse effect of steep slope on the amount of the infiltrated water. Both the sorptivity coefficient and hydraulic conductivity values decrease with increase in tension values. Decreasing rate of sorptivity coefficient in high slopes was greater than that in low slopes but decreasing rate of hydraulic conductivity in low slopes was greater than that in high slopes. With increase in tension values the sorptivity coefficient values tend to a constant value. Also with increase of slope gradient from 0 to 40 degrees, decrease of hydraulic conductivity in 0 tension (saturated condition) was 3.7 times more than that in 15 cm tension. The results of transient state experiment correspond to those of other researches^{3,5,23}. The reasons for increase of sorptivity coefficient and decrease of hydraulic conductivity with increase of slope gradient can be explained as follows: 1) In steep slopes, the downslope component of each soil particle weight causes slight compression of soil and decrease of pores dimensions. Therefore,

Table 1. Some selected soil physical properties of the experimental site.

Parameter	Slope gradient (degree)				
	0	1	20	30	40
Bulk density (g/cm^3)	1.66	1.67	1.68	1.68	1.69
Particle density (g/cm^3)	2.58	2.57	2.57	2.57	2.58
Sand (%)	39.3	38.4	38.9	38.1	40.2
Silt (%)	38.1	37.2	37.6	39.2	38.5
Clay (%)	22.6	24.4	23.5	22.7	21.3
Porosity (%)	35.66	35.02	34.63	34.63	34.5

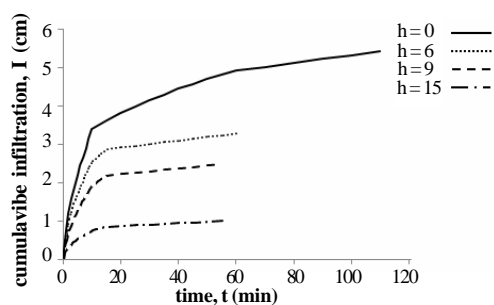


Figure 1. Cumulative infiltration vs. time (0 degree of slope gradient).

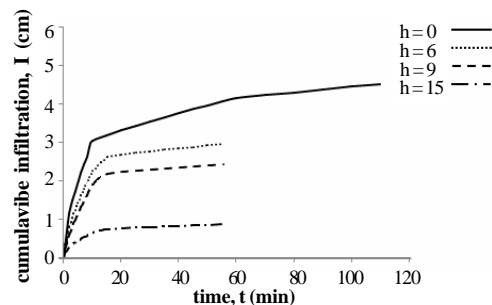


Figure 2. Cumulative infiltration vs. time (40 degrees of slope gradient).

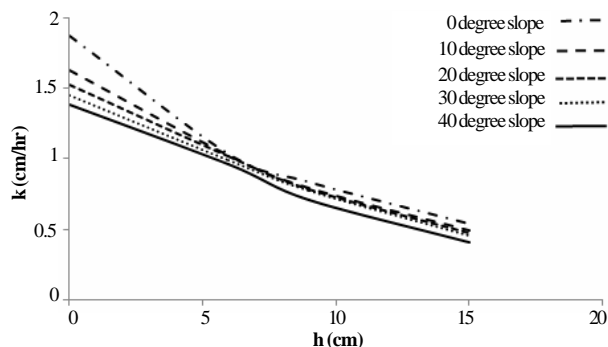


Figure 3. Mean hydraulic conductivity, $K(h)$ at different slope gradients.

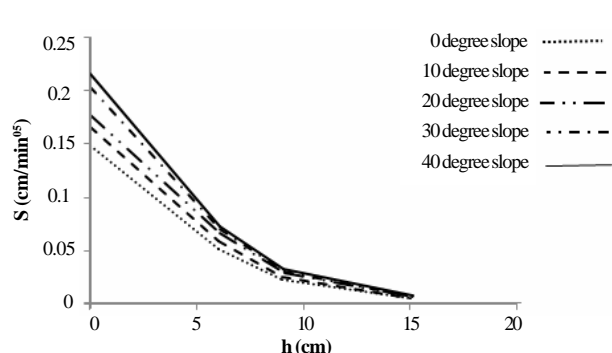


Figure 4. Mean sorptivity coefficient, $S(h)$ at different slope gradients.

the amount of flow through the soil decreases with decrease of pores dimensions due to increase of slope gradient. 2) Soil particles arrangement in sloping surface is different from that in level surface^{5, 20, 22}. In sloping surface soil particles arrangement has higher regularity than that in level surface. Therefore, total porosity in sloping land is less than that in level land, which causes reduction in hydraulic conductivity value.

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