Environmental and Earth Sciences Research Journal
Vol. 6, No. 3, September, 2019, pp. 119-124
Journal homepage: http://iieta.org/journals/eesrj

Effects of Pressure Heads and Soil Bulk Density on Infiltration Characteristics of Vertically Inserted Moistube Irrigation

Youliang Peng, Xiaogang Liu*, Yifei Zhu, Qiliang Yang

Faculty of Agricultural and Food, Kunming University of Science and Technology, Kunming 650500, China

Corresponding Author Email: liuxiaogangjy@126.com

https://doi.org/10.18280/eesrj.060304

Received: 16 May 2019
Accepted: 27 July 2019

Keywords:
moistube irrigation, pressure head, soil bulk density, infiltration rate, cumulative infiltration, regression analysis

ABSTRACT

Moistube irrigation is a new water-saving technology. In order to explore the effect of pressure head and soil bulk density on water infiltration of moistube irrigation in vertical inserting mode, a series of indoor infiltration experiments were performed. Three pressure heads (H_1:1.0 m, H_2:1.5 m and H_3:2.0 m) and three soil bulk densities (D_1:1.00 g·cm^{-3}, D_2:1.15 g·cm^{-3} and D_3:1.30 g·cm^{-3}) were set, with a total of 9 treatments, each processing 3 replicates. Wetting body was selected as observation object to record the change of wetting front profile. During the infiltration process, the Mariotte bottle was recorded and the wetting front at each time point was depicted on the side of the soil box. After 124 h of infiltration, the contours of wetting front at each time point depicted on the side of the soil box were copied onto the checkerboard to calculate the soil wetting volume, and the cumulative infiltration was calculated according to the Mariotte bottle scale and inner diameter. Studying the relationship between wetting volume, infiltration rate and cumulative infiltration with infiltration time, and the impacts of pressure head and soil bulk density on infiltration coefficient K and infiltration index α. The results showed that the pressure head and soil bulk density had significant effects on the infiltration capacity of moistube irrigation. Compared with D_1, steady infiltration rates and cumulative infiltration of moistube irrigation decreased by 14.27%-33.61% and 12.92%-30.54% with the increase of soil bulk density. Compared with H_1, steady infiltration rate and cumulative infiltration of moistube irrigation increased by 17.12%-37.02% and 18.67%-40.31% with the increase of pressure head. The wetted soil volume decreased with the increase of soil bulk density, while increased with the increase of pressure head. The changing process of cumulative infiltration with time was accorded with Kostiakov model. The infiltration coefficient K was positively correlated with pressure head and negatively correlated with soil bulk density, while the infiltration index α was negatively correlated with pressure head and positively correlated with the soil bulk density. Regression analysis showed that the influence of pressure head on infiltration index α was greater than soil bulk density, and the influence of pressure head on infiltration coefficient K was less than soil bulk density. The water infiltration capacity of moistube irrigation increased with the increase of pressure head, while decreased with the increase of soil bulk density. The results can provide a scientific basis for the practical application of moistube irrigation in agriculture.

1. INTRODUCTION

Moistube irrigation (MI) is a new technology in the field of agriculture developed by using semi-permeable membrane technology [1-3]. Compared with other irrigation methods, MI has smaller head loss, and the flow index is larger [4-5]. Compared with surface irrigation technology, MI can reduce surface evaporation and soil deep leakage, and has the advantages of water saving. At the same time, it also has the characteristics of strong anti-clogging performance, low operating cost and improving soil environment in crop root zone [6-11].

The MI outflow is mainly affected by pressure head, soil bulk density and soil texture [12]. Pressure head, as one of the main driving forces of MI, is an important factor affecting water infiltration [13-14], and plays a significant role in MI. the soil wetting volume, cumulative infiltration, average infiltration rate, horizontal wetting front of soil and vertical migration distance will increase with the increase of pressure head [15-17]. Soil bulk density has a great influence on soil physical properties and erosion resistance. With the increase of soil bulk density, the greater the infiltration resistance of water in soil, the smaller the soil wetting volume and diffusion coefficient [6, 12, 19]. As a new water saving technology, MI is more focused on horizontal layout, while the infiltration law of vertical MI suitable for fruit trees and economic trees with wide distance crops is still insufficiency.

In order to further clarify the water infiltration characteristics of vertical MI, the method of laboratory simulation test was adopted to study the effects of pressure head and soil bulk density on the infiltration characteristics of vertical wetting irrigation so as to provide scientific basis for rational use of moistube.

2. MATERIALS AND METHODS

2.1 Experimental materials

The obtained soil samples were air-dried, compacted and evenly mixed, and then passed through a 2 mm sieve. Soil particle size distribution was analyzed and determined using laser particle size analyzer (Mastersizer-2000, UK). The particle size composition of soil natural heap laying down was 0.050 mm<d<2.000 mm, 0.002 mm<d<0.050 mm and d<0.002 mm, accounting for 16.80 %, 28.63 % and 54.57 % of the total soil sample, respectively. Soil type was determined to be clay loam according to the international soil classification system, its initial moisture content was 3.78 %.

2.2 Experimental device

The test device is mainly composed of soil box, moistube, rubber hose, Mariotte bottle and lifting support. The soil box (40 cm×40 cm×45 cm) was used to fill the soil sample for testing. The 3rd generation moistube (Shenzhen Moistube Irrigation Co., Ltd, China) is a polymer semi-permeable membrane with inner layer thickness of 0.06 mm and micropore diameter ranging from 10 to 900 nm. The arrangement of moistube is vertical, the upper end was connected with rubber hose, and the lower end is closed by rubber plug. Rubber hoses was used to connect moistube and Mariotte bottle. The Mariotte bottle is used to provide a constant head of water with a scale on it to calculate the cumulative infiltration. Lifting bracket realizes water head regulation.

2.3 Experimental design and method

Three pressure heads and three soil bulk densities were set in the experiment. The three pressure heads were H_1:1.0 m, H_2:1.5 m and H_3:2.0 m, respectively. Three soil bulk densities were D_1:1.00 g·cm^{-3}, D_2:1.15 g·cm^{-3} and D_3:1.30 g·cm^{-3}, respectively. This experiment consisted of 9 treatments in total, and each treatment was repeated three times. The length of moistube was 30 cm and the effective seepage length was 25 cm. The moistube was vertically inserted into the plexiglass soil box, its upper end was 5 cm away from the soil surface, and the horizontal distance between the two sides and the two walls of plexiglass soil box was 1 cm. The filling height of plexiglass soil box was 40 cm. During the process of infiltration, Mariotte bottle readings were recorded every 2 h during the first 12 hours of infiltration, once every 4 h from 12 hours to 48 hours, once every 8 h after that, and wetting fronts at each point of time were depicted on the side of soil box. After 124 hours of infiltration, the experiment was completed. The cumulative infiltration and infiltration rate were calculated according to Mariotte bottle calibration scale and the inner diameter. The infiltration rate is the cumulative infiltration amount per unit time.

The wetting front migration curve and the volume of the rotating body were used to calculate the volume of the wetting body at different time, and the formula should be as Eq. (1):

$$V = \frac{1}{4}\pi\int_0^a f^2(x)dx \tag{1}$$

where, V is the soil wetting volume, cm^3; a is the maximum depth of wetting front, cm; f(x) is the fitting function of wetting front migration, and the correlation coefficient with measured curve is more than 0.9.

$$f(x) = \sum_{i=0}^{n} b_i x^i \tag{2}$$

where, x is the depth of the wetting front, cm; b_i is the fitting coefficient of f(x); n is a positive integer.

3. RESULTS

3.1 Effect of pressure head and soil bulk density on wetting volume

The relationship between soil wetting volume and infiltration time was simulated by quadratic polynomial, and the absolute coefficients were greater than 0.99 (Table 1). Compared with the measured soil wetting volume, after infiltrating 24 hours, the relative error of the simulated values ranged from 0.24 % to 6.11 %, with an average of 2.56 %, while the average relative error was only 1.64 % and 1.54% after 48 hours and 124 hours of infiltration. It indicated that the simulation result was better, and the quadratic polynomial of infiltration time could well describe the change process of wetting volume in vertical moistube irrigation (MI). The soil wetting volume decreased with the increase of soil bulk density under the same pressure head and infiltration time, but increased with the increase of pressure head at the same soil bulk density and infiltration time.

Table 1. Wetted soil volume under different pressure heads and soil bulk densities

Pressure head	Soil bulk density	Fitting formula	R^2	Measured value (cm^3)			Simulation value (cm^3)			Relative error(%)		
				24h	48h	124h	24h	48h	124h	24h	48h	124h
H_1	D_1	V=-0.51t^2+156.06t+31.06	0.9995	3486.77	6382.05	11651.74	3478.31	6329.17	11422.35	0.24	0.83	1.97
	D_2	V=-0.17t^2+86.40t-43.15	0.9976	1847.36	3564.20	8023.62	1929.44	3699.85	7972.34	4.44	3.81	0.64
	D_3	V=-0.12t^2+58.15t+30.74	0.9994	1321.50	2445.29	5307.28	1356.00	2540.14	5358.90	2.61	3.88	0.97
H_2	D_1	V=-0.55t^2+190.76t-220.98	0.9986	4082.58	7671.22	14926.15	4034.87	7645.95	14827.31	1.17	0.33	0.66
	D_2	V=-0.17t^2+91.54t+79.58	0.9994	2212.01	4032.91	8725.12	2176.65	4073.50	8759.31	1.60	1.01	0.39
	D_3	V=-0.24t^2+83.98t+199.20	0.9965	2058.98	3682.12	7125.79	2075.95	3675.07	6907.35	0.82	0.19	3.07
H_3	D_1	V=-0.41t^2+173.5t+135.71	0.9972	4159.08	7701.38	15870.06	4059.86	7504.32	15247.14	2.39	2.56	3.93
	D_2	V=-0.05t^2+93.91t+212.72	0.9990	2352.27	4568.86	10958.85	2438.96	4609.90	11119.76	3.69	0.90	1.47
	D_3	V=-0.31t^2+107.81t-137.18	0.9993	2137.46	4362.55	8430.33	2268.01	4308.71	8366.29	6.11	1.23	0.76

Notes: V: soil wetting volume, cm^3; t: Infiltration time, h.

3.2 Effect of pressure head and soil bulk density on infiltration rate

Figure 1 showed that the infiltration rate was relatively high within 24 hours of the beginning of infiltration, but decreased rapidly. Then the infiltration rate gradually approached stable with the infiltration time, and reached stability after 48 hours. Pressure head and soil bulk density had significant effects on steady infiltration rate. Compared with H_1, the steady infiltration rates of H_2 and H_3 increased by 17.13 %-25.47 % and 28.25 %-37.02 % respectively. Compared with D_1, the steady infiltration rate of D_2 and D_3 decreased by 14.27 %-19.75 % and 28.89 %-33.62 % respectively. Therefore, the steady infiltration rate enhanced with the increase of pressure head, but decreased with the increase of soil bulk density.

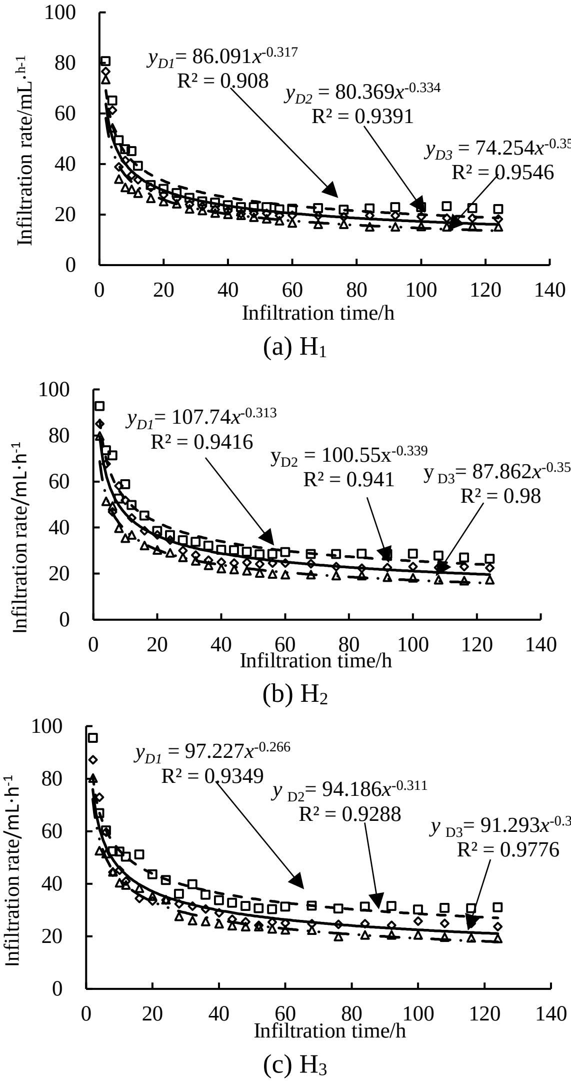

Figure 1. Curve between infiltration rate and time under different pressure heads and soil bulk densities

3.3 Effect of pressure head and soil bulk density on cumulative infiltration

Accumulated infiltration is often used to characterize infiltration capacity before reaching a stable infiltration rate [20]. The absolute coefficients of power function fitting of cumulative infiltration and infiltration time were greater than 0.9 (Figure 2). The experimental results showed that the cumulative infiltration increased with the increase of infiltration time under the same water head and soil bulk density. After 128 h infiltration, the cumulative infiltration of H_2 and H_3 increased by 18.67 %-26.47 % and 30.49 %-40.31 % respectively when compared with H1. Compared with D_1, D_2 and D_3 decreased the cumulative infiltration by 12.92 %-18.97 % and 25.31 %-30.54 % respectively. The results indicated infiltration rate increased with pressure head, but decreased with soil bulk density.

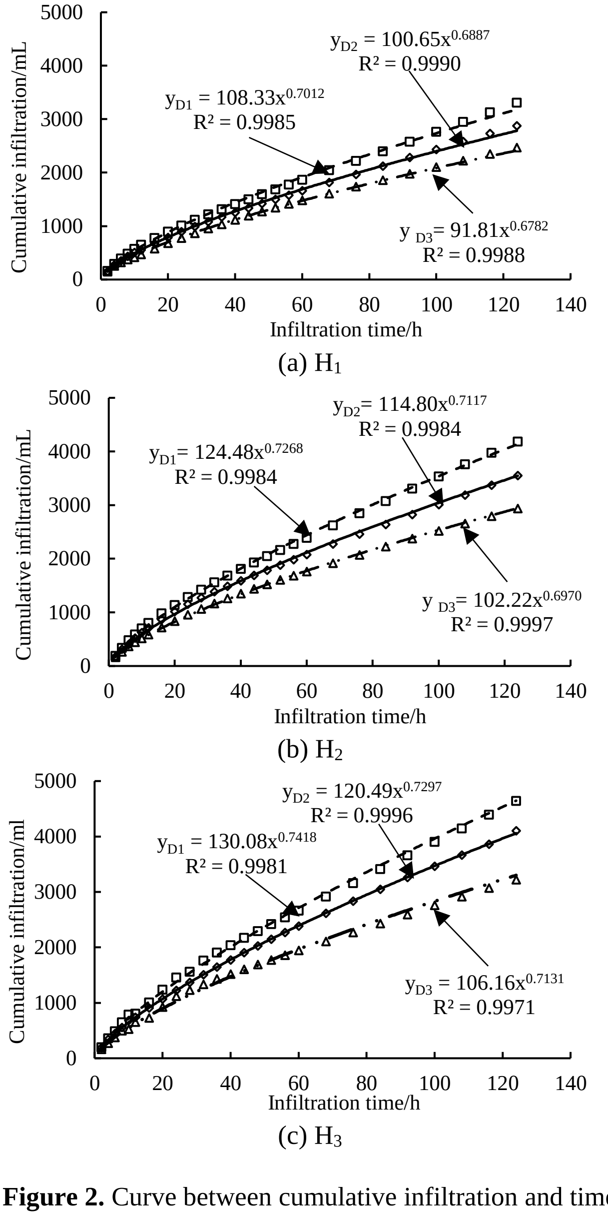

Figure 2. Curve between cumulative infiltration and time under different pressure heads and soil bulk densities

3.4 Effect of pressure head and soil bulk density on infiltration model parameters

The infiltration process was described by Kostiakov soil infiltration model. Although the model is an empirical model, the parameters could also repress some characteristics of soil infiltration. The formulas for calculating infiltration rate and cumulative infiltration amount are should be as [21]:

$$i_t = i_1 t^{-\alpha} \tag{3}$$

$$I_t = \int_0^t i_t dt = \int_0^t i_1 t^{-\alpha} dt = \frac{i_1}{1-\alpha} t^{1-\alpha} = K t^{1-\alpha} \tag{4}$$

where, i_t is the infiltration rate, measured by the thickness of water layer per unit time (cm·h^{-1}); i_1 is the infiltration rate at the end of the first unit time; t is the infiltration time (h); α is the infiltration index, reflecting the attenuation rate of soil infiltration capacity; I_t is the cumulative infiltration amount at t time (cm); K is the infiltration coefficient (cm·h^{-1}), reflecting the cumulative infiltration at the end of the first unit period after infiltration.

By fitting and analyzing the data processed in this experiment, the results showed that the absolute coefficients were above 0.99 (Table 2). The infiltration index α decreased with the increase of pressure head, and the infiltration coefficient K increased with the increase of pressure head (Table 2). Compared with H_1, the α values of H_2 and H_3 decreased by 5.84 %-8.57 % and 10.85 %-13.59 %, while the K values increased by 11.34 %-14.91 % and 15.63 %-20.08 %, respectively. When the pressure head was the same, the infiltration index α increased with the increase of soil bulk density, while the infiltration coefficient K decreased with the increase of soil bulk density. Compared with D_1, the α values of D_2 and D_3 increased by 4.18 %-5.53 % and 7.70 %-11.12 %, while the K values decreased by 7.09 %-7.78 % and 8.78 %-11.90 %, respectively.

Table 2. Infiltration parameters under different pressure heads and soil bulk densities

Pressure head	Soil bulk density	Parameters		
		Infiltration coefficient K	Infiltration index α	R^2
H_1	D_1	108.33	0.2988	0.9985
	D_2	100.65	0.3113	0.999
	D_3	91.81	0.3218	0.9988
H_2	D_1	124.48	0.2732	0.9984
	D_2	114.80	0.2883	0.9984
	D_3	102.22	0.3030	0.9997
H_3	D_1	130.08	0.2582	0.9981
	D_2	120.49	0.2703	0.9996
	D_3	106.16	0.2869	0.9971

3.5 Regression analysis

It was found that the infiltration index α, as well as the infiltration coefficient K, were exponentially related to the pressure head and soil bulk density. The relationships could be expressed as:

$$K = Ae^{BH+CD} \tag{5}$$

$$\alpha = Ge^{EH+FD} \tag{6}$$

where, A, B, C, G, E and F are coefficients; K is infiltration coefficient, cm·h^{-1}; α is infiltration index; H is pressure head, m; D is soil bulk density, g·cm^{-3}.

Logarithms were taken on both sides of formula (5) and (6) and the fitting model is obtained (K=176.296e$^{0.169H-0.629D}$), α=0.247e$^{-0.134H+0.315D}$). The determination coefficients R^2 were 0.96 and 0.99, indicating good fitting effect.

T-test [22] was adopted to analyze the influence degree of various influencing factors on the cumulative infiltration. And the test value t was 2.776 when a=0.05. The t values of B, C, E and F were 7.576, -8.435, -18.050 and 12.709 respectively, and the absolute values were all greater than 2.776. It showed that the effects of pressure head and soil bulk density on infiltration index α and coefficient K were significant. The influence of pressure head on the infiltration index α was greater than that of the soil bulk density, while the influence of soil bulk density on the infiltration coefficient K was greater than that of the pressure head. A value of t greater than 0 indicates that the influencing factor is positively correlated with the infiltration index α and the infiltration coefficient K, otherwise it is negatively correlated. Therefore the infiltration index α was negatively correlated with pressure head but positively with soil bulk density. While the infiltration coefficient K was positively correlated with the pressure head but negatively with the soil bulk density.

4. DISCUSSION

There are many factors affecting water infiltration in moistube irrigation, including salinity, pressure head, soil bulk density, initial soil moisture content, burial depth and so on [8, 12, 15, 23]. In our study, the effects of pressure head and soil bulk density on water infiltration character in vertical moistube irrigation were studied. It is found that the cumulative infiltration, steady infiltration rate, soil wetting volume and infiltration coefficient K increased with the increase of pressure head, while the infiltration index α decreased, which is basically consistent with the relevant research results [12, 15]. However, Ma et al found that the infiltration coefficient K increased firstly and then decreased with the increase of pressure head [24], which was not completely consistent with the results of our study. The pressure head (only 5-60 cm) was small in Ma's experiment. With the increase of pressure head, soil infiltration interface changed from compact to relatively stable, and finally to compact [24], so the infiltration coefficient K increased first and then decreased. While the pressure head of this experiment was larger (1-2 m), which changed the condition of the soil at the infiltration interface, resulting in the increase of the infiltration coefficient K with the increase of pressure head. This may because pressure head changed of soil structure at infiltration interface and increased water conductivity. On the other hand, with the increase of pressure head, more gravity potential energy was transformed into dynamic potential energy, making the attenuation rate of infiltration capacity slow down, so the infiltration index α decreased with the increase of pressure head. In practical production, the output flow of moistube irrigation can be controlled by adjusting the height of pressure head.

Increasing soil bulk density hindered water infiltration, which was basically consistent with the relevant research results [12, 20]. In our study, it was found that infiltration index α increased with the increase of soil bulk density, but the cumulative infiltration, steady infiltration rate, soil wetting volume and infiltration coefficient K decreased. This was because with the increase of soil bulk density, the infiltration of soil water was mainly accomplished by macropore. Therefore, the soil air permeability and water storage capacity reduced with the increase of soil bulk density, which could lead to the decrease of infiltration rate, cumulative infiltration volume and wetting volume. In addition, the smaller the gas-phase ratio, the greater the infiltration resistance and the faster decline of the infiltration capacity with the higher the soil bulk density. In our study, the effects of pressure head and soil bulk density on water infiltration characteristics of vertical moistube irrigation were studied, but the effects of initial soil moisture content, burial depth, salinity, infiltration time and water infiltration of moistube irrigation and its impact degree need to be further studied.

5. CONCLUSIONS

(1) Under the vertical moistube irrigation, the soil wetting volume had a quadratic polynomial relationship with infiltration time. The soil wetting volume decreased with the increase of soil bulk density and increased with the increase of pressure head.

(2) The infiltration rate was relatively fast in the initial stage of infiltration. With the lengthening of infiltration time, the infiltration rate decreased gradually, and the infiltration rate tended to be stable around 48 hours.

(3) The infiltration rate and cumulative infiltration rate were in accordance with the power function of exponential negative and exponential positive respectively under the vertical moistube irrigation. the larger the soil bulk density, the smaller the cumulative infiltration and the infiltration rate, and the larger the pressure head, the higher the cumulative infiltration and the infiltration rate.

(4) The cumulative infiltration of vertical moistube irrigation with time conformed to the Kostiakov model, and the infiltration coefficient K was negatively correlated with soil bulk density but positively correlated with pressure head, while the infiltration index alpha was positively correlated with soil bulk density but negatively correlated with pressure head.

ACKNOWLEDGMENT

This research was supported by the National Natural Science Foundation of China (Grant No. 51979133, Grant No. 51769010, Grant No. 51109102 and Grant No. 51469010).

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