Influence of Bulk Density and Initial Soil Water Content on Capillary Rise in Sandy Loam

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Capillary rise from the ground water is a process which plays a very significant role in meeting the evapotranspiration needs of crops. Simultaneously, salts are also brought up to the soil surface along with the soil water and they can damage the crop if present in excess. It is also very well known that water present in either limited or excess quantity, either directly or indirectly, reduces plant growth and crop yield. With proper management techniques, crops can be grown successfully even without irrigation, under shallow and medium water table conditions [11]. The rate of capillary rise and the water transmission properties are dependent on the physical characteristics of the soil layers above the water table [3, 5, 9]. The most important of these, besides the soil texture, are the pore space and the initial soil water content of the overlying layers, the available information on which is scanty. A study was, therefore, carried out to observe the influence of these two parameters on capillary rise in sandy loam soil.

Materials and methods

Soil was collected from the surface 15 cm of Top block 1, Indian Agricultural Research Institute Farm, New Delhi. It was air dried and passed through a 2 mm sieve. The important physical and chemical properties of the soil are given in Table 1.

Soil columns, 100 cm in length and 30 cm in diameter, were prepared in cylinders made of galvanized iron sheets (18 gauge). Soil was compacted to obtain 1.4, 1.6 and 1.8 g cm^{-3} bulk densities and maintained at 3, 5 and 7 per cent (by weight) initial soil water contents. Measured amount of soil was spray mixed thoroughly with required quantity of water and allowed to equilibrate for 24 h in air tight polythene bags before compaction. Soil was compacted in the cylinders at 10 cm layer increments. The top of the soil column was sealed with a polythene sheet to prevent evaporation. The bottom of the column was provided with 10 mesh wire screen base. A constant water table was maintained at 96 cm distance from the top of the column. It was practically not possible to compact soil to 1.8 g cm^{-3} bulk density at 3 per cent initial soil water content so this treatment was excluded.

Tensiometers were placed at 16, 32, 48, 64, 80 and 88 cm heights above the water table. The changes in soil water tension were monitored with respect to time and height. The frequency of observations was increased when the boundary of rising water reached any tensiometer level.

Unsaturated capillary conductivity was computed by the formula

$$K(\Theta) = g : \frac{\partial \Phi}{\partial z} \tag{1}$$

where $K(\Theta)$ is the unsaturated capillary conductivity ($cm \cdot day^{-1}$) at soil water content Θ ($cm^3 \cdot cm^{-3}$), g is the flux of water moving upward ($cm \cdot day^{-1}$) and $\partial\Phi/\partial z$ is the total water potential gradient, $\partial\Phi$ representing the change in the total water potential over a vertical distance ∂z.

The flux is given by $$g = \int \frac{\partial \Theta}{\partial t} \cdot \partial z \tag{2}$$

where, $\partial\Theta$ is the change in the soil water content over a time interval ∂t.

Tensiometer data were used to calculate the total water potential gradient and the soil water content, the latter with the help of soil water characteristic curve, at various depths and times.

Table 1

Physical and chemical properties of the studied soil

1. Mechanical composition		5. Soil water retention characteristics		
soil separates	%		Tension (bar)	Soil water content (% by weight)
(a) Sand	74			
(b) Silt	15			
(c) Clay	11		0	27.3
Textural class	Sandy loam		0.1	21.1
2. pH (1 : 2.5 suspension)	7.75		0.33	11.2
			0.8	7.6
			2.0	5.7
3. Organic matter, %	0.44		5.0	4.8
4. CEC me/100 g soil	13.0		10.0	4.1
			15.0	3.5

Results and discussion

There was a stabilization of tension values in the soil columns in most of the treatments within ten days. However, in the column having 1.4 $g \cdot cm^{-3}$ bulk density at 3 per cent initial soil water content, the time taken was almost twenty days. The capillary rise curves were found to flatten out with height and time. This was due to the active capillaries becoming progressively finer as water moved away from the water table [4, 12]. Fig. 1 shows the effect of compaction on capillary rise as observed through falling tension due to the water front coming in contact with the tensiometer placed at various depths. The effect of initial soil water content when the capillary rise was considered as a function of total time taken for equilibrium by the tensiometer at each point is shown in Fig. 2.

Compaction: The rate of capillary rise increased initially with decrease in bulk density. At 5 per cent initial soil water content, the time gap before the initiation of the fall in tension at 16 cm height was 0.25, 0.66 and 1.75 h in case of 1.4, 1.6 and 1.8 g cm^{-3} bulk density treatments, respectively. A similar trend was also observed in the other two levels of initial soil water content (Fig. 1).

As the height of the soil above the water table increased, the rate of capillary rise slowed down. However, the capillary rise reached the upper layers earliest in the densest soil column. The time taken for the capillary rise to reach the tensiometer placed at 88 cm above the water table was 216, 105 and 59 h in columns at 5 per cent initial soil water content and packed to 1.4, 1.6 and 1.8 g cm^{-3} bulk density, respectively.

The capillary rise was initially faster in soil columns at lower bulk density in layers in contact with the water table because of the greater percentage of larger pores. This facilitated a faster entry of water and a faster rate of wetting front advance [2, 5]. Compaction resulted in the reduction of total porosity, increase in total number and relative volume of smaller pores and decrease in the total number and relative volume of larger pores. This was responsible for the enhancement of capillary rise at higher bulk densities [7, 8, 10].

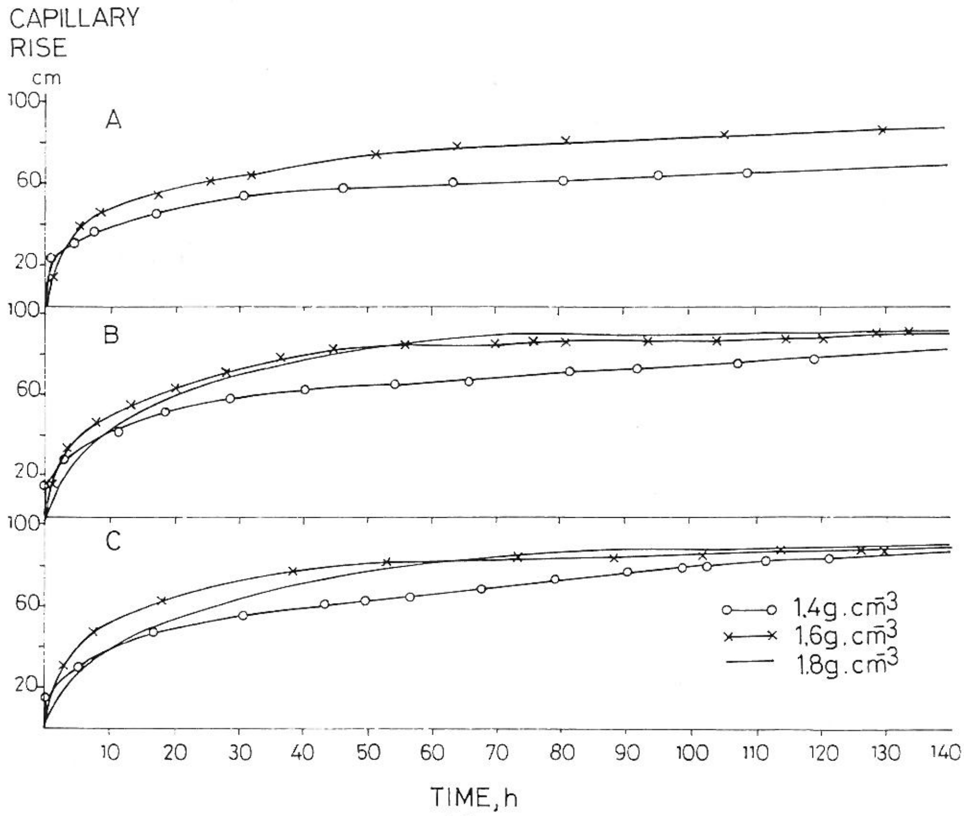

Fig. 1.

Effect of compaction on the capillary rise (A: 3, B: 5 and C: 7 per cent initial soil water content)

It is evident that although water may enter the soil column of lower bulk density faster, it will take more time to fill the large pore spaces present in the soil. In case of higher bulk densities, the capillary pores are more and the total pore space less, hence, the capillary front reaches the uppermost layers earlier in those treatments.

Initial soil water content: Capillary rise was affected by the initial soil water content of the soil to an appreciable extent. On considering the period taken for water to rise from the water table to the tensiometer, it was observed that the rate was fastest in columns at 7 per cent followed by 5 and 3 per cent initial soil water contents. The time taken by the water boundary to reach the topmost tensiometer was 491, 216 and 139 h in the soil columns packed at 1.4 g cm^{-3} bulk density having 3, 5 and 7 per cent initial soil water content. In columns packed to 1.6 g cm^{-3} bulk density, the time taken by the capillary water to reach the top was 130, 110 and 100 h at 3, 5 and 7 per cent initial soil water contents, respectively. Increase in the rate of capillary rise with increase in initial soil water was reported by [6, 8]. This was not observed in case of 1.8 g cm^{-3} bulk density treatments. The moving water boundary took 88 h to

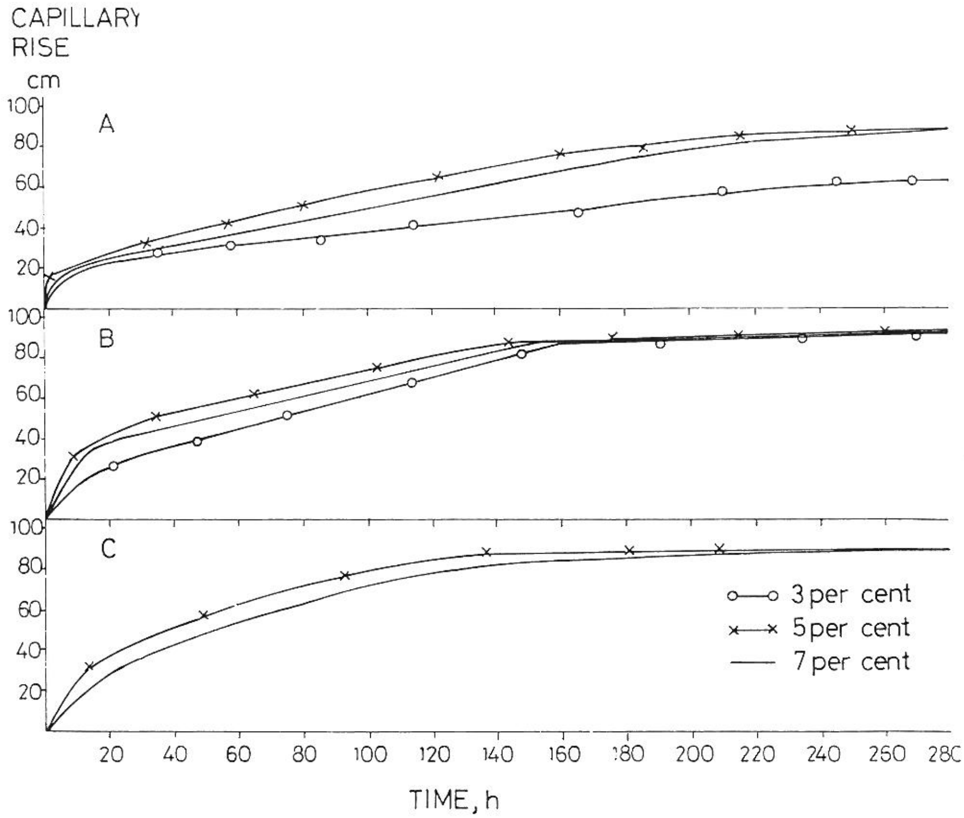

Fig. 2.
Effect of initial soil water content on the capillary rise (A: 1.4, B: 1.6 and C: 1.8 g · cm^{-3} bulk density)

reach the uppermost layer in columns at 7 per cent initial soil water content. The time taken was 59 h in columns at 5 per cent initial soil water content. The movement in the soil column at 7 per cent initial soil water content was probably slower due to the moving water encountering more resistance in the smaller pores. A higher initial soil water content is expected to result in fewer larger pores and more of smaller pores available for capillary rise at high bulk densities.

The time taken by the tensiometers to attain a steady tension value, was least in soil columns having 5 followed by 7 per cent initial soil water content at all levels of bulk densities. Columns having 3 per cent initial soil water content took maximum time in reaching equilibrium (Fig. 2). In columns compacted at 1.4 g cm^{-3}, the time taken was 546, 250 and 276 h at 3, 5 and 7 per cent initial soil water contents, respectively, for the uppermost layer. The time was 164, 130 and 150 h in columns compacted at 1.6 g cm^{-3} bulk density treatments at 3, 5 and 7 per cent initial soil water contents, respectively. A similar observation was made in columns at 5 and 7 per cent initial soil water contents, packed to 1.8 g · cm^{-3} bulk density.

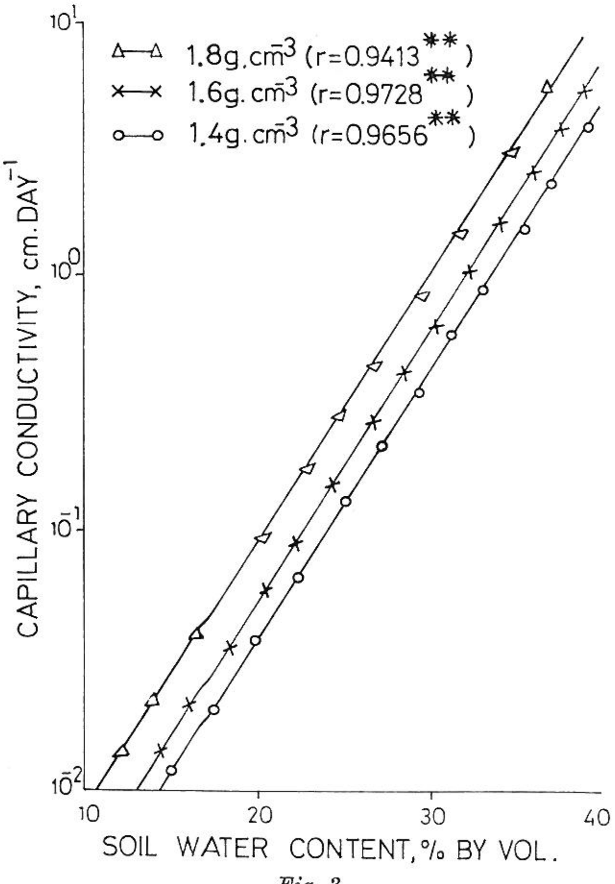

Fig. 3.
Effect of compaction on the unsaturated capillary conductivity of sandy loam soil
** significant at 1%

Table 2

Soil water suction profiles in soil columns at different bulk densities and initial soil water contents

Treatments	Tension (cm of water column)					
	Height of tensiometers above water table, cm					
	16	32	48	64	80	88
1.4 g cm^{-3} bulk density						
3%	060	065	170	200	235	265
5%	035	080	150	180	235	275
7%	070	105	150	170	240	270
1.6 g cm^{-3} bulk density						
3%	115	130	145	155	190	210
5%	120	145	165	175	185	215
7%	110	135	160	165	210	225
1.8 g cm^{-3} bulk density						
5%	170	185	190	200	215	230
7%	175	190	205	215	225	235

This may be attributed to the interaction of two factors — the magnitude of the capillary forces and the nature of available pores. In columns at 3 per cent initial soil water content, maximum pore space is devoid of water, hence, a longer time is required to fill the pores. The suction gradient is relatively steeper in the columns at 5 per cent compared to 7 per cent initial soil water content. Though the available pore space is less in columns at 7 per cent initial soil water content, it consists mostly of smaller pores offering a greater resistance to movement of water. As a result of this interaction, the time for equilibrium was the least in soil columns at 5 per cent initial soil water content.

Capillary conductivity: Compaction of the soil was observed to increase the capillary conductivity of soil (Fig. 3). This is due to an increase in capillary pores as a result of compaction [8]. Compaction causes reduction in air permeability but increase in water permeability by increasing membrane flow around clusters [1].

Capillary conductivity increased with increase in soil water content and this relationship was described satisfactorily by

$$K(\Theta) = a \exp. b\Theta \tag{3}$$

where, a and b are constants and $K(\Theta)$ is the capillary conductivity at soil water content Θ. 'r' values for the lines fitted to the computed data have been shown in Fig. 3. All r values were significant at 1 per cent level. Calculated values of a were 7.6×10^{-4}, 4.2×10^{-4} and 3.1×10^{-4}, b were 0.1027, 0.1123 and 0.1040 for bulk densities 1.8, 1.6 and 1.4 g cm^{-3}, respectively.

Soil water suction profiles: Tension values observed after 30 days of equilibrium indicated that compaction resulted in a more uniform soil water suction profile (Table 2). The initial soil water content had no significant influence on their ultimate values.

The higher capillary conductivity at any specific soil water content due to compaction along with a faster capillary rise resulted in a more uniform soil suction profile.

Conclusion

In the investigation carried out under zero evaporation conditions, the rate of capillary rise was faster initially in columns at lower bulk density. The moving water boundary reached earlier the uppermost layers of the soil columns packed at higher bulk densities. Capillary rise tended to be faster in columns with higher initial soil water content. Equilibrium in the tension values was reached earliest in columns at 5, followed by 7 and 3 per cent initial soil water contents. Capillary conductivity increased with increase in bulk density and soil water content. The relationship between capillary conductivity and soil water content was satisfactorily described by an exponential function.

Summary

Capillary rise was studied in sandy loam soil in columns 30 cm in diameter and 100 cm in height. Soil was compacted to three bulk densities 1.4, 1.6 and 1.8 g cm^{-3}, at three initial soil water contents of 3, 5 and 7 per cent by weight. A constant water table at 96 cm depth was maintained in each soil column. The top of the soil column was sealed with a polythene sheet to prevent evaporation. Tensiometers were installed at heights of 16, 32, 48, 64, 80 and 88 cm above the water table.

The rate of capillary rise was faster in the lower bulk density treatments initially. The water front, however, reached the upper layers in columns with higher bulk density in a shorter time. Capillary rise in general, was more rapid in soil columns at higher initial soil water content except in the highest bulk density treatment. Equilibrium of tension was attained earliest in the columns packed at 5, followed by 7 and then 3 per cent initial soil water contents. Capillary conductivity computed from the flux and the hydraulic gradient values, was found to increase with increase in bulk density and soil water content. Dependence of the capillary conductivity on the soil water content was satisfactorily described by an exponential relationship.

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