浸透率 測定과 再分配時의 土壤水分흐름의 推定

Infiltration Measurement and Prediction of Soil Water Flow During Redistribution

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摘　要

地表에서 土壤속으로 흐르는 물(水分)의 浸透率을 同心圓管形 浸透計(double-ring infiltrometer)를 使用하여 測定하였다. 內部管과 外部管의 浸透率을 比較함으로써 침투율 측정시 침투계 바깥쪽으로 흐르는 水平方向의 흐름을 예상할 수 있으며, 서로 다른 初期含水條件에서 침투율을 측정, 비교함으로써 초기 함수 상태의 침투율에 대한 영향을 고찰하였다. 측정치를 분석한 결과 예상한 대로 바깥쪽으로 흐르는 水平方向의 토양 수분으로 인하여 外部管에서의 침투율이 內部管에서 보다 平均 90% 컸으며, 또 初期 含水量이 작은 경우가 큰 경우보다 침투율이 컸다.

浸透가 끝난 후 再分配時의 토양 수분 흐름은 水理傾斜를 檢討함으로써 推定하였다. 水平 및 鉛直方向의 水理傾斜는 多端 텐시오미터(multiple-depth tensiometer)를 사용하여 토양속의 공극水壓을 測定하여 계산하였다. 水理傾斜를 檢討한 결과 再分配時 水平方向의 토양수분 흐름은 一定한 方向이 아니라 경우에 따라서 圓管 침투계의 中心쪽으로 또는 바깥쪽으로 흘렀다. 이는 토양의 物理的 性質이 場所에 따라서 均一하지 않았음에 基因한 것이라 判斷된다. 再分配時 水平 및 鉛直方向의 平均水理傾斜의 比率을 檢討한 결과 時間이 경과할수록 이 比率이 감소 되었으며, 또 깊이가 깊어질수록 감소하였다. 이는 즉 時間이 지날수록, 깊이가 깊어질수록 토양수분 흐름의 水平方向 成分이 감소한다는 것을 나타낸다.

I. Introduction

Infiltration, which is an important part of the hydrologic cycle, is the process of water entry into the soil, generally, through the soil surface and vertically downward.[2,3,8] Infiltration rate is the flux passing through the surface and flowing into the soil profile. The infiltration rate is one of the most important properties of soil ; it directly influences the surface renoff and ground water recharge rates. Therefore, to determine accurate infiltration rate is necessary for planning water related projects. Several investigators conducted research on infiltration by either field study,[4] analytical approach,[6] or numerical approach.[10]

In order to minimize the influences of lateral flow on infiltration rates during infiltration measurements in the fields, we use a double-ring infiltrometer. However, the influences of lateral flow on infiltraion rates are still expected. Much research has been done in the field concerning the infiltration rate. Ahuja,

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et al.[1] studied the lateral flow during infiltration measurement and concluded that the lateral flow was practically eliminated when a outer ring (buffer zone) of larger than 90 cm diameter was employed. Murabayashi and Fok[9] mentioned that some of the high infiltration rates of abondoned pineapple fields in Hawaii may be influenced by lateral flow when a double-ring infiltrometer is used.

In this paper, field data which were collected during the summers of 1976 and 1977 with a double–ring infiltrometer and multiple depth tensiometers were used.

The objectives of this study are : (1) to analyze the effects of lateral flow and the initial soil moisture condition on the infiltration rates measured by a double-ring infiltrometer, and (2) to analyze the soil water pressure head gradients both in lateral and vertical directions during redistribution stage from the measurements of the multiple–depth tensiometers.

Ⅱ. Materials and Methods

Field measurement

Field experiment were carried out during the summers of 1976 and 1977 by Green, et al.[7]

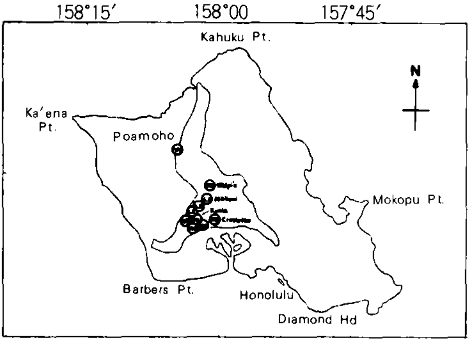

Fig. 1. Field measurement sites within an Oxisols area, Oahu, Hawaii. After Green et al

Table-1. Soils, study sites and site designations (after Green, et al., 1982)

Soil Series (1)	Taxonomic Unit (Soil Family) (2)	Location (3)	Replicate (4)	Site Designation (5)
WAHIAWA	Clayey, kaolinitic, isothermic (Tropeptic Eutrustox)	U.H. Experiment Farm,	Lower	W1-Ⅰ
		Paomoho	Upper	W1-Ⅱ
		Pineapple Research	North	W2-Ⅰ
		Institute Waipio	South	W2-Ⅱ
		OP 157, Kunia	Plot 1	W3-Ⅰ
			Plot 2	W3-Ⅱ
			Plot 3	W3-Ⅲ
			Plot 4	W3-Ⅳ
LAHAINA	Clayey, kaolinitic, isohypothermic (Tropeptic Haplustox)	OP 246, Mililani	West	L1-Ⅰ
		(Sewage Effluent	East	L1-Ⅰ
		Experiment Site)		
		OP 221, Kunia	East	L2-Ⅰ
			West	L2-Ⅱ
		OP 146, Kunia	West	L3-Ⅰ
			East	L3-Ⅱ
MOLOKAI	Clayey, kaolinitic, isohyperthermic (Typic Torrox)	OP 146, Kunia	North	M1-Ⅰ
			South	M1-Ⅱ
		HSPA Expt. Sta.,	North	M2-Ⅰ
		Field C, Kunia	South	M2-Ⅱ
		OP 410, Crestview	East	M3-Ⅰ
			West	M3-Ⅱ

The field measurements were conducted on soils of the Molokai (Typic Torrox), Lahaina (Tropeptic Haplustox), and Wahiawa (Tropeptic Eutrustox) series in the island of Ohau, Hawaii. Infiltration and redistribution measurements were made on two to four experimental sites, 10 m to 20 m apart, at each of nine different locations, giving a total of 20 experimental sites. Fig.1. shows the field measurement sites. Table1 shows soils, study sites, and site designations. The taxonomic unit is abroader category than the soil family. Detailed descriptions of the soils are given by Green, et al.[7)] All test sites were in sugarcane fields with tilled A_p horizons 30 cm to 40 cm deep. Site preparation involved leveling of the soil surface followed by shallow hoeing and final leveling as used by Chong, et al.[5)]

Infiltration measurements were conducted with a double-ring infiltrometer of which the diameters of the inner ring and outer-ring (buffer zone) were 30cm and 120cm, respectively. The infiltrometer rings were installed by the method of ahuja, et al.[1)]

The process of infiltration was initiated by ponding water in the inner ring and in the outer ring to a level 2.0 cm above the soil surface (with te exception of 8.0 cm at OP157, Kunia), which was maintained throughout te duration of run by means of float valves. The soil within the rings was covered with pieces of burlap to prevent direct water impact and subsequent disturbance of soil surface. The water was supplied from two different supply tanks fitted with 0.6 cm glass tubes to show the water level inside. Initial wetting of the profile was accomplished with an infiltration run on dry soil. The water level was read at 1 to 15 minute intervals in each tank, as a measure of cumulative infiltration in the inner ring and the outer ring. After a redistribution period of one day, multiple-depth tensiometers, which have the prous cups for all desired depths on one stem, were installed at the center of the inner ring at the middle of the outer ring. Multiple-depth tensiometer installation procedures followed those used by Ahuja, et al.[1)]

The porous cups of the multiple-depth tensiometer were located at 7.6, 22.9, 45.7, 76.2, 106.7, and 137.2 cm from the ground surface in most measurements, but in some installations the cup depths were 10, 20, 30, 40, and 50 cm or 10, 20, 40, 60, 80, and 100 cm.

After the tensiometer installation, redistribution of soil water was allowed to proceed for another two days, followed by an infiltration run on the moist soil. Water application was continued approximately one hour beyond the time that an apparent steady infiltration rate was observed.

After the water supply was cut off, zero time for redistribution is defined to be the time when water in the inner ring had just disppeared from the ground surface. The soil water tensions (negative pressures) during the redistribution period were obtained from the multiple-depth tensiometer readings. The redistribution periods lasted 6 to 26 days.

The soil surface inside the rings was covered with a plastic sheet during redistribution to prevent evaporation. A 2cm thick styrofoam sheet was placed on the plastic sheet to reduce extreme changes in soil temperature. A canopy

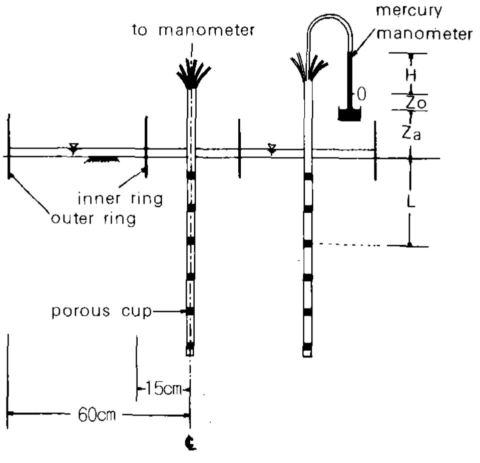

Fig. 2. Schematic diagram of double-ring infiltrometer and multiple-depth tensiometer

was installed aobve the experimental setup to prevent rainfall from entering the ring.[5)] Fig. 2 illustrates the double-ring infiltrometer and multiple- depth tensiometers used during the field measurements.

Calculations and analyses

The steady state infiltration rates were obtained by dividing the volume of the water which entered into the soil during the last period of time by that period of time (about 60 minutes). The infiltration rates of both inner ring and outer ring were calculated both for the dry run and wet run.

As shown on Fig. 2, each porous cup of the tensiometer was connected to separate monometer. As tension develops, mercury rises in the manometer tube. When the equilibrium between the water and mercury is at a height H above the zero point of the mercury tube, the tensions of soil water at the given depth is

$$\psi = H-(L+Z_0+Z_a+H/13.6)+13.6\ Z_0 \cdots\cdots (1)$$

in which ψ =tension in cm of water, H=tensiometer reading in millibar (≒ cm of water), L= depth in cm from ground surface to porous cup, Z_0=distance in cm from free surface of mercury in the pot to zero point of mercury tube, and Z_a=distance in cm from ground surface to free surface of mercury in the pot.

After computing all the tensions of inner ring and outer ring using Eq.(1), lateral hydraulic gradients were calculated. The distance between two tensiometers of the inner ring and the outer ring was 37.5cm. Therefore, the lateral hydraulic gradients of each depth at each time were obtained by dividing the differences between the pressure heads of the inner ring and outer ring by 37.5cm, i.e.,

$$\frac{dh}{dr}=\frac{h_i-h_o}{37.5} \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

in which dh/dr is the lateral hydraulic gradient, h_i-h_o is the total head of the inner ring minus that of the outer ring. In some locations the depths of the tensiometer porous cups were different at the inner ring and at the outer ring. In these cases, the tensions of the outer ring at the same depth as the inner ring were computed by interpolation of the two adjacent values of outer ring tensions.

In addition, the vertical hydraulic gradients of the inner ring at different depths and different times were calculated to compare the horizontal hydraulic gradients with the vertical hydiaulic gradients. The vertical hydraulic gradients were obtained by dividing the differences of total head at different depths by the distance of two depths, i.e.,

$$\frac{dh}{dz}=\frac{h_{i+1}-h_i}{z_{i+1}-z_i} \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

in which dh/dz is the vertical hydraulic gradient, $h_{i+1}-h_i$ is the total head at depth z_{i+1} minus that at depth z_i.

Then the average ratios of lateral to vertical hydraulic gradients in soil layers of different thicknesses located at different depths were calculated for some selected locations. They are calculated by

$$\text{average ratio}=\frac{\text{ave.}dh/dr}{\text{ave.}dh/dz} \cdots\cdots\cdots\cdots (4)$$

In the computation of average lateral hydraulic gradients, the thicknesses of A_p and B_2 horizons were considered as separate regions. The steel ring infiltrometer penetrated into the ground 15 cm to 20 cm deep, therefore, only the thickness of the A_p horizon below 15 cm or 20 cm from the ground surface was considered.

Fig. 3. shows an example of soil horizons for claculating the lateral and vertical hydraulic gradients. The lateral hydraulic gradient at depth z_i can be calculated by Eq. (2), and the vertical one by Eq. (3). In this location, the average lateral and vertical hydraulic gradients of the a_p horizon are calculated from tensions at depths z_2 and z_3, and those of B_2 horizon are calculated from tensions at depths z_3,

z_4, and z_5.

After all the computations were completed graphs were drawn. Graphs of the tension versus depth relation at different time were drawn in order to see te distribution of tensions in accordance with soil depth and redistribution time, and to compare the difference of tensions between the inner ring and outer ring. In addition, the graphs of average ratios of the lateral to vertical hydraulic gradients versus time at differt depths were drawn.

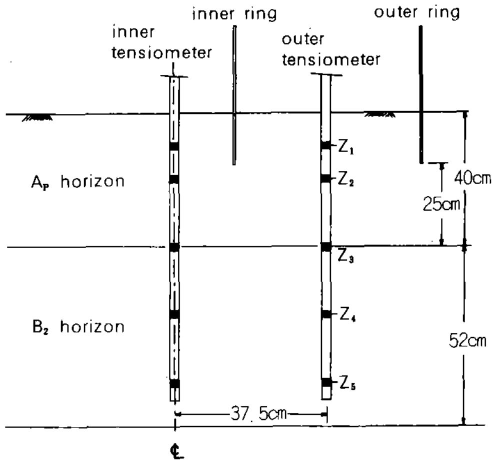

Fig. 3. Soil horizons and tensiometer locations of OP 221, Kunia, West

Ⅲ. Results and Discussions

Infiltration rate

Steady state infiltration rates and elapsed time to reach the steady state flow are listed in Table 2. At site W2, the steady state during dry run could not be reached because the soil was so porous that the water in the supply tanks ran out in less than 30 minutes. However, the wet runs were made at this site after

Table-2. Steady state infiltration rate and the elapsed time to reach steady state flow

Site designation (1)	Date of field test (2)	steady state infiltration rate Dry run (m/day)		Wet run (m/day)		Flapsed time to steady flow(hours)		Remark (9)
		Inner (3)	Buffer (4)	Inner (5)	Buffer (6)	Dry run (7)	Wet run (8)	
W1-Ⅰ	June 15, 1977	2.76	1.78	0.77	1.18	2.41	3.03	
W1-Ⅱ	June 15, 1977	4.24	4.15	0.45	2.50	1.38	2.95	
W2-Ⅰ	July 5, 1977	–	–	2.69	6.27	–	1.21	During dry run water ran short. Extremely porous.
W2-Ⅱ	July 5, 1977	–	–	2.49	7.27	–	1.74	
W3-Ⅰ	June 3, 1976	0.66	0.78	0.66	0.70	3.37	3.47	
W3-Ⅱ	June 3, 1976	2.03	1.62	0.78	0.74	1.61	2.64	
W3-Ⅲ	June 3, 1976	2.86	2.70	0.97	1.06	1.47	1.06	
W3-Ⅳ	June 3, 1976	0.53	0.97	0.54	1.05	3.74	3.28	
L 1-Ⅰ	July 27, 1977	5.83	6.62	2.58	5.70	1.12	1.58	Extremely porous.
L 1-Ⅱ	July 27, 1977	7.80	4.65	4.38	6.33	1.73	1.42	
L 2-Ⅰ	Aug. 3, 1977	2.28	2.61	1.51	1.20	3.51	1.53	
L 2-Ⅱ	Aug. 3, 1977	1.52	1.98	0.73	1.04	2.06	2.00	
L 3-Ⅰ	Aug. 10, 1977	0.67	0.65	0.40	0.53	2.37	2.64	
L 3-Ⅱ	Aug. 10, 1977	0.45	0.68	0.20	0.55	3.19	2.54	
M1-Ⅰ	July 13, 1977	1.00	0.90	0.64	0.85	4.28	2.83	
M1-Ⅱ	July 13, 1977	0.49	1.42	0.26	0.78	2.15	1.60	
M2-Ⅰ	July 23, 1977	1.06	1.61	0.36	0.95	3.63	3.45	
M2-Ⅱ	July 23, 1977	1.82	2.27	0.61	0.93	1.43	1.99	
M3-Ⅰ	Aug. 17, 1977	1.73	2.14	0.88	1.00	2.36	2.60	
M3-Ⅱ	Aug. 17, 1977	1.36	1.92	1.26	1.31	2.81	1.51	

3 days of redistribution as at other sites.

During infiltration measurement the steay state was reached within 1.12 to 4.28 hours from the beginning of the wetting in the dry run and 1.06 to 3.47 hours in the wet run. On some locations the times to reach the steady state in the wet run were longer than those in the dry run. On other locations, they showed the reverse. The time to reach the steady state varied because of the differences of soil properties such as porosity, water content, and grain size on the different locations.

In the dry runs, the steady state infiltration rates of the inner ring ranged from 0.45 m/dry to 7.8 m/day, and those of the outer ring ranged from 0.65 m/day to 6.6 m/day. In the wet runs, the steady state infiltration rates of the inner ring ranged from 0.2 m/day to 4.4 m/day, and those of outer ring ranged from 0.5 m/day to 7.3 m/day.

The steady infiltration rates of the dry runs were much higher than those of the wet runs. It is quite reasonable because the water contents of soil in the dry runs should be smaller than those in the wet run. Also, it is likely that there is some structural consolidation of tilled surface soils after the dry runs. Thus, the infiltration rates of the wet run represent the steady state infiltration rates for the consolidated soil. For some reasons such as abrupt changes of soil structures, or some instrumetal errors, the infiltration rates of the outer ring were smaller than those of inner ring in two locations out of a toatl of 20 locations of experiments. Except these two locations, the infiltration rates of the outer ring were higher than those of the inner ring by 4% to 452% (average 90%).

The higher infiltration rates of the outer ring suggests the existence of lateral flow during infiltration measurements. The infiltration rates can be adjusted for the lateral flow by the method of Ahuja, et al.1)

Horizontal hydraulic gradients

Concerning the soil water tensions, the values varied at different depths and elapsed time during the redistribution period. The soil water tensions ranged from -82.1 cm to 245.5 cm of water in the inner ring, and from -80.7 cm to 279.3 cm of water in the outer ring. The negative tensions mean positive pressures.

At the beginning of redistribution, the tension showed negative values. This means during the first period of time that the soil was saturated with water. These tensions become larger and larger as depth increases and time passes. The negative tension values began to change into positive values within 20 minutes from the shallower depth. Then other negative values changed into positive values gradually as the depth became deeper and deeper.

The lateral flux was expected to indicate flow from inner ring to outer ring. However, the horizontal hydraulic gradients did not show that all the lateral flow was from inner ring to outer ring during redistribution. Nearly half of the horizontal hydraulic gradients of different soil depths at different elapsed times showed negative values, which means the water flowed from outer ring to inner ring. Some extremely large or small values of the horizontal hydraulic gradients and inward flux might be caused by non-homogeneous and anisotrophic properties of soil, and broken columns of mercury manometer during the measurement. How-

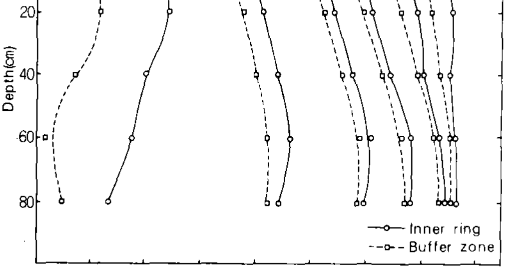

Fig. 4. Comparison of tension versus depth of inner ring and buffer zone (OP 221, West)

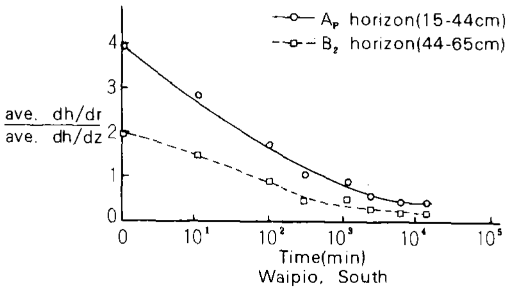

Fig. 5. Aberage ratio of lateral to vertical hydraulic gradients versus redistribution time.

ever, further study is needed to find out the causes of them.

Fig. 4. illustrates the tension versus depth relation of inner ring and outer ring at different times at OP 221, Kunia, West.

Ratio of lateral to vertical hydraulic gradients

The values of vertical hydraulic gradients varied from -0.5 to 1.95. Some extrmely large values might be caused by broken column of mercury manometer during the field measurement.

Fig. 5 illustrates the aveage ratio of lateral to vertical hydraulic gradients versus time at Waipio, South. The figure shows that the average ratios of lateral to vertical hydraulic gradients decrease as time elapses, and they will approach zero. Also, it shows that the ratios in the A_p is greater than those in the B_2 horizon.

Ⅳ. Conclusions

On the basis of the reslults obtained from present study the following conclusions were drawn :

1. It is confirmed in general that : (1) the infiltration rates of the outer ring were greater than those of the inner ring during the infiltration measurement by a double-ring infiltromenter ; and (2) the steady state infiltration rates on dry soil were greater than those on wet soil.
2. During the redistribution period, the horizontal hydraulic gradient showed the existence of lateral flow ; however, they did not show that all the flux was outward. Nearly half of the lateral hydraulic gradients showed inward flux possibly because of the heterogeneity of soil properties.
3. The average ratios of the lateral to vertical hydraulic gradients decrease as the redistribution time elapses and those in the shallow horizon are greater than those in the deeper horizon.

Further research is required to figure out the causes of the inward flux during the redistribution period, and to compare the measured resluts with the values which may be predicted by using various infiltration equations.

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