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CONSIDERABLE DIFFERENCE BETWEEN THE VELOCITY OF WATER PERCOLATION AND THAT OF SOIL MOISTURE PROFILE IN A LYSIMETER

by

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SYNOPSIS

The main purpose of this study is to obtain experimental data as to the actual water moving velocity in a lysimeter and the shifting velocity of soil moisture content there as well. The former was determined from the behavior of the peak concentration of heavy water (D_2O) injected artificially, while the latter was determined from the data of suction and resistance in soil. The actual movement of water due to a rainfall was only 0.06cm/h (10cm/week) in the topsoil layer and from 0.018 to 0.023cm/h (3 to 4cm/week) in the subsoil layer. This velocity at the subsoil layer showed a good coincidence with the estimated value based on the data of the amount of percolation at the bottom and the soil conditional parameters, such as void ratio and the degree of saturation of pore-water. The shifting velocity of the high moisture peak was found to be from 8 to 12cm/h in the topsoil layer and from 0.8 to 2cm/h in the subsoil layer, either of which was nearly one hundred times greater than that of actual water movement. This fast phenomenon is basically explained by diffusion wave and kinematic wave characteristics of water in unsaturated soils.

INTRODUCTION

We are confronted by a serious soil pollution due to many hazardous wastes, such as heavy metals, compound organic materials, insect killers and so on. The behavior of water and soil solutions with rainfall must be studied in order to determine how soils are being polluted and to know what to do for soil environment protection as well as the proper way to go about it.

The purpose of this study is to show experimental data on unsaturated percolation in a lysimeter. The actual moving velocity of pore-water was determined by the use of heavy water (D_2O) as a tracer, while the shifting velocity of the vertical profile of water (soil moisture) content was determined by the measurement of suction and resistance R in soil.

Recently, very interesting facts concerned with unsaturated percolation have been reported (e.g. Andersen & Sevel (1), Hatano (3), and Pickens & Grisak (9)) such as very wide diffusion of soil solutions accompanying percolation, a very quick response of groundwater level to a rainfall compared with very slow movement of solutions both at the upper unsaturated layer and in the groundwater.

To explain these facts, either unnatural, large soil-water diffusivity and unsaturated (hydraulic) conductivity, or a "by-pass" model has been introduced. Muraoka (6) has reviewed the literature on diffusivity and unsaturated conductivity. There have been several different "by-pass" models ((4),(10)). Hatano (4) has reviewed the work as to "by-pass" effect and "source-sink" effect of aggregated soils. Some reports have emphasized the heterogeneous properties of soils including cracks, gaps, water paths and so on. Zimmermann et al. (13) considered the two different water volumes in pores, the stationary one, and the draining one, to explain their experimental results.

From field study, the difference between the actual movement velocity of water and the movement velocity of soil moisture profiles in fields has been discovered. The former velocity was determined from the data of tritium profile (1) or D_2O profile (13), while the latter velocity was obtained by the regular measurement of soil moisture profile by the neutron method ((1),(2)). According to those field studies, the latter velocity was about ten times larger than the former. Zimmermann et al. (13) suggested the existence of wave properties to understand the behavior of the soil moisture profile. Yamada & Kobayashi (12) have attempted to apply kinematic wave theory to explain the great difference between the two velocities, and they succeeded in doing so without considering the "by-pass" effect.

However, there have been no precise data which directly support the idea by Yamada & Kobayashi, so such data have been eagerly awaited. Of course, the above field work ((1),(2),(13)) on moisture profile provides considerable corroboration for the idea; however, the soil moisture data were too complex, due to the many rainfalls and weather conditions, and the time intervals of the data seem too long to pursue the precise soil moisture response to a rain. Wilson and Gelhar (11) calculated the profiles of moisture and soil solution during unsaturated infiltration and showed that the movement rate of the solute front was smaller than that of the moisture front. Their results showed a good agreement with the field test data by Miller et al. (5); however, the data obtained by Miller et al. was as to Chloride displacement, which did not necessarily coincide with the actual water movement in soils. To check the above idea, one must know the actual moving velocity of water and that of moisture profile under a controlled rainfall and evaporation condition. The present experiment was conducted based on this conception, and our results support the basic idea of Yamada and Kobayashi's work.

PROCEDURES

To study unsaturated percolation phenomena through soil, a cylindrical lysimeter, 1.7m wide and 2.3m high, was used. The conditions around the lysimeter were controlled automatically: soil temperature in the lysimeter, 18 - 20 °C; room temperature, 25 °C in the daytime or 20 °C at night; and room humidity, 60 % (7). The soil was packed in the lysimeter as shown in Fig. 1 and Table 1. The soil conditions shown in Table 1 are the data of two days after a rainfall. No plant was grown in the topsoil. The soil was Light Colored Ando Soils with 0.45mm in median diameter and 0.48mm in standard deviation of particle-size distribution. The specific gravities of the soil samples were around 2.5; their void ratios were 2.0 - 2.7; water (soil moisture) contents were 70 - 90%; and the range of their saturation was 65 - 100%. The deeper soil samples tended to be more packed and to hold more water in their pores.

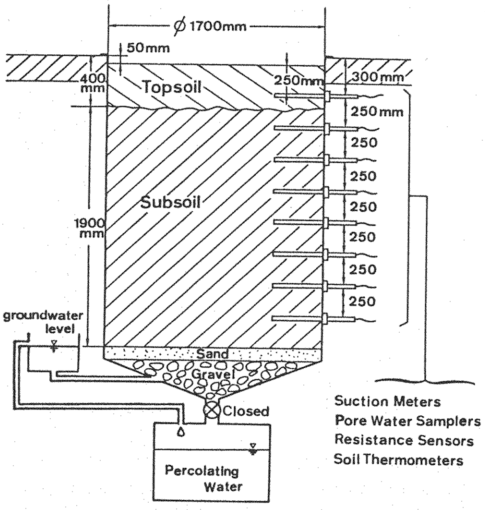

Fig. 1 Lysimeter schematic diagram

Table 1 Soil conditional parameters through the lysimeter

Sumple		Gs	e	w(%)	Sr(%)
East	surface	2.54	2.67	67.7	64.6
East	18 cm	2.53	2.87	72.5	64.3
East	50 cm	2.51	2.37	86.9	93.3
East	75 cm	2.55	2.35	85.3	92.5
East	100 cm	2.54	2.45	84.8	83.8
East	125 cm	2.56	2.28	82	91.5
East	150 cm	2.57	2.42	83.1	87.6
East	175 cm	2.64	2.38	83.1	89
West	surface	2.46	2.66	67.4	64.5
West	18 cm	2.48	2.72	73.4	68.7
West	50 cm	2.5	2.41	86.7	91.6
West	75 cm	2.69	2.36	86.2	93
West	100 cm	2.48	2.32	85.5	93.9
West	125 cm	2.54	2.22	78.8	90.3
West	150 cm	2.73	2.04	77.9	97.5
West	175 cm	2.53	2.03	78.9	99

Gs: Specific gravity; e: Void ratio;
w: Water content; Sr: Saturating index

Pore-water samplers (ceramic cups, 20mm in diameter and 60mm in height), soil thermometers, and resistance sensors were buried at 0.25m intervals from the soil surface. Soil solutions were collected without disturbing soil conditions. Suction meters were buried at 10cm, 30cm, 55cm, 80cm, 105cm and 130cm deep from the surface. A tank to collect the percolating water was set under the lysimeter, and the amount of percolating water was measured automatically.

Figure 2 shows the artificial rainfall pattern adopted in this experiment and the time variation of percolating water in the tank. Sixty five litters of pure water has been poured on the soil surface within 5 minutes at the appointed time every Monday morning.

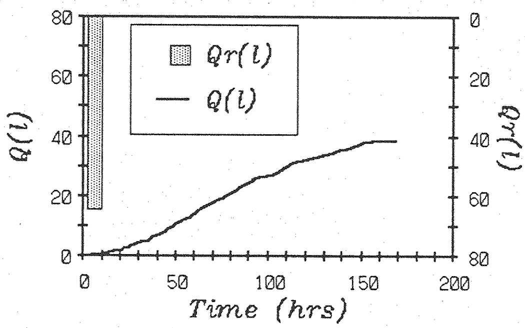

Fig. 2 Artificial rainfall pattern repeated every week and the time dependence of percolating water amount at the bottom

After checking for a steady weekly percolation pattern, we poured 651 of pure water containing heavy water of 14000ppm and NaCl of 75ppm onto the soil surface. This week was defined as the zero week of the experiment. (To keep the soil as clean as possible and the soil moisture as steady as possible, a particular amount of pure water had been poured into the lysimeter once a week regularly for about nine years.) After that, 651 of pure water has been poured on it every Monday morning as mentioned above. By pursuing the time variation of vertical profile of heavy water concentration in the lysimeter, one can determine the actual moving (percolating) velocity of the pore-water.

The soil temperature and resistance in the lysimeter have been monitored automatically. The suction has been read at the appointed time intervals. The pore-water has been collected every Thursday. The D_2O concentration of the pore-water samples was determined by the D_2O analyzer (Shokou Tsusho), and that of Cl^- by the autoanalyzer (Technicon).

RESULTS

The time variation of percolating water at the bottom has been repeating the same pattern every week, and the amount of percolating water during a week has been almost steady at around 371, as shown in Fig. 2. Therefore, the evaporation during a week is calculated to have been around 281.

Figure 3(a) shows the weekly variations of D_2O concentration at the eight sampling sites, and Fig. 3(b) shows those of Cl^- concentration, respectively. It is noticeable that Cl^- moved downwards much slower than D_2O. The D_2O peak moved downwards at about 10cm/week up to 25cm deep, at about 4cm/week up to 50cm deep, and at about 3cm/week up to 100cm deep; the Cl^- peak, on the other hand, moved downwards at about 3cm/week up to 25cm deep, at 2cm/week up to 50cm deep, and at about 1.5cm/week up to 100cm. Precisely speaking, Cl^- peak has not yet reached the depth of 100cm at 50 weeks from the beginning of the experiment.

The D_2O peak has moved downwards about twice as fast as that of Cl^-. In the pre-experiment, the same results were obtained in a small soil-packed lysimeter, measuring 23cm in height and 10cm in diameter. On the other hand, Cl^- was found to move downwards with D_2O, when beads were adapted as a porous substance in the same lysimeter (7). The D_2O is believed to be the best tracer of water (H_2O) movement in soils. From these facts, we can say that Cl^- can not be a tracer of

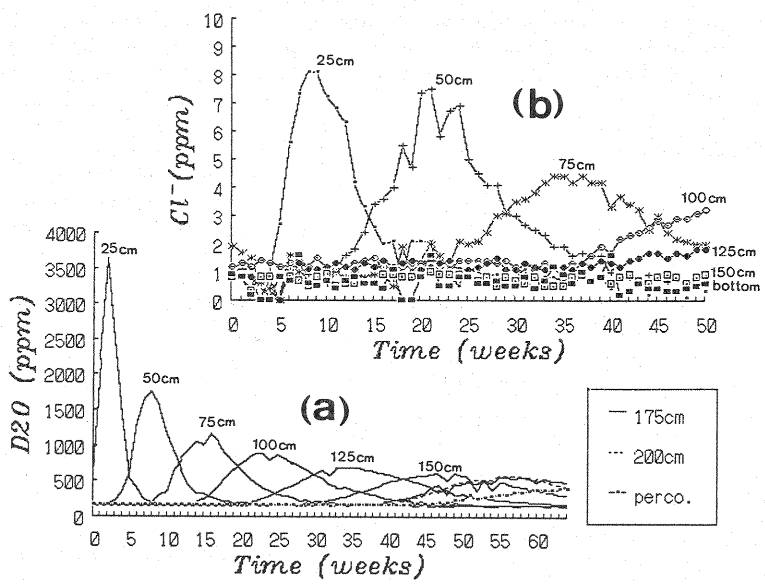

Fig. 3(a) Weekly fluctuations in D_2O concentration at the eight sampling sites
(b) Weekly fluctuations in Cl^- concentration at the eight sampling sites

pore-water movement in natural soils, where the electrochemical activity of the soil surface, such as adsorption and desorption, is believed to affect the movement of solutions significantly (3).

Figure 4 shows the weekly variation of the vertical profiles of D_2O concentration in the lysimeter. Those profiles were drawn based on the D_2O concentration data which were measured from the samples taken every week from the eight sampling sites at 25cm intervals. The location of the peak D_2O concentration went down each week, and its peak became lower and its vertical profile flatter with the week. For instance, at 15 weeks from the beginning of this experiment, the peak of the profile reached about 70cm deep and the peak concentration decreased about one-tenth, compared with the initial concentration and its

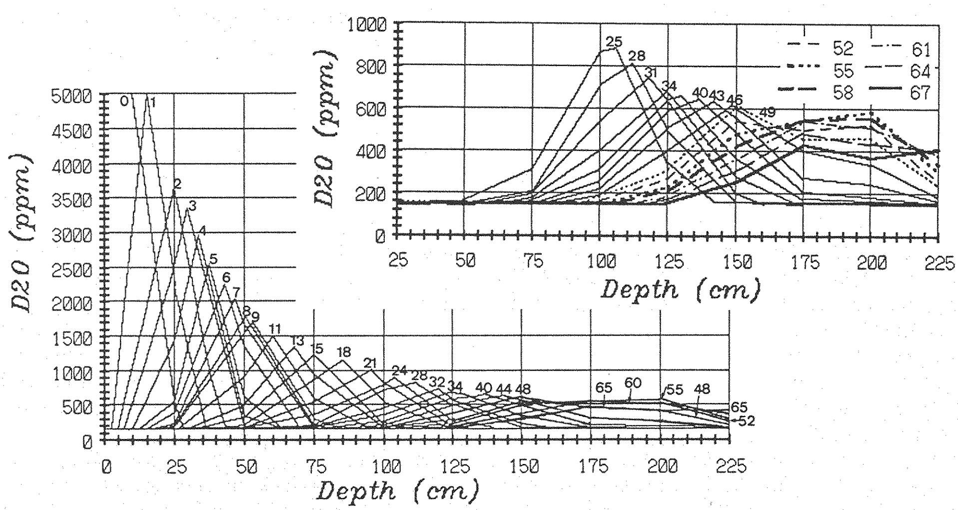

Fig. 4 Weekly variations of the vertical profile of D_2O concentration in pore-water (The numbers within figures indicate the number of weeks elapsed since D_2O of 14000 ppm was injected on the soil surface.)

distribution spread at 50cm wide; at 30 weeks, the profile shifted its peak to a depth of about 115cm with a height of about 750ppm, enlarging its width to about 90cm; at 45 weeks, the profile shifted its peak to about 145cm deep with the height of about 600ppm and an even greater width of more than 125cm wide; the front of the profile reached the very bottom of the lysimeter (225cm deep). After about 43 weeks from the beginning of the experiment, the vertical profiles of D_2O concentration showed different patterns from those of until 43 weeks at the depth range of 150cm to 225cm, that is, the peak concentration appeared earlier at 200cm deep than at 175cm deep. We will discussed this phenomenon elsewhere.

The shifting of the vertical profile of moisture content in soil due to a rainfall has been pursued by the use of suction meters and resistance meters. Suction depends on soil moisture, though its hysteresis dependence has been reported; however, it depends on neither the type nor the concentration of solutions. But in spite of being a very good indicator of moisture content change under low soil moisture conditions, the resistance (R) depends on moisture content and type and concentration of solutions as well. Hence, it is much more difficult to estimate the moisture content from the data of resistance in soil than from the suction data.

Figure 5 shows the three weeks straight time variations of suction h (mmHg) at the six measurement points, and Fig. 6 shows the 24-hour time variations of the electric resistances R(kilo-ohm) since a rainfall at six depth points. The suction and resistance R began to fall several minutes or 30 or more minutes after a rainfall, then rose again. The times of this fluctuation depended on the

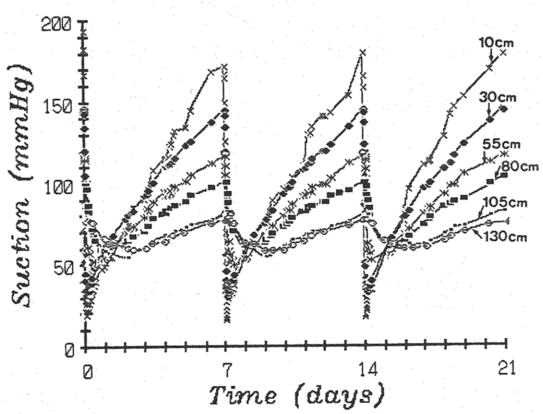

Fig. 5 Time variations of suctions at the six measurement sites (For three weeks straight)

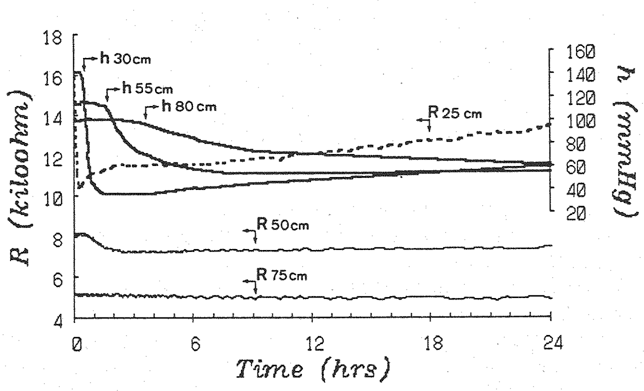

Fig. 6 Time variation of the resistances and suctions at three depth points (For 24 hours after a rainfall)

depth. The suction and resistance at each point have been repeating almost the same weekly patterns, indicating that the vertical profile of moisture content has a weekly pattern. The responses were faster in shallower locations. The response of resistance was slightly faster than that of suction in topsoil as we can see from Fig. 5 and Fig. 6; however, the response of resistance was very little, judging from the data on the depth of 75cm beneath where moisture content was always high. Thus, the suction data will be used for the following discussion about the shifting of the moisture content pattern.

DISCUSSION

First of all, let us consider the results as to time variations of suctions, correlating them vertically. Figure 7 provides a basis for discussing the behavior of pore-water during a week, such as the time variation of high moisture content region due to a rainfall, or the dependence of pore-water flux on the total head gradient. Here, we think of a pore-water balance discretely as shown in Fig. 7, because the data have been taken at 25cm intervals. L_i indicates the thickness of ith layer, h_i = water potential in ith layer ($h_i > 0$: suction head, $h_i < 0$: hydrostatic head), A_i = total head gradient between ith and (i+1)th layers, F_i = pore-water flux from ith layer to (i+1)th one. The flux is expressed as follows:

$$F_i = k_i A_i, \quad (A_i = (h_{i+1} - h_i)L_i^{-1} + 1) \qquad (1)$$

in which k_i = unsaturated conductivity of ith layer.

Figure 8 shows the time dependence of vertical profiles of water potential which were drawn based on the data of h_i at six measuring points. From this figure, we can say that the low suction portion (i.e., high moisture content portion) due to a rainfall descended from the surface to the depth of 130 cm within a day. After the high moisture content peak was passed, each layer began to dry. However, this does not necessarily mean that the pore-water flux was always oriented upwards in the drying process.

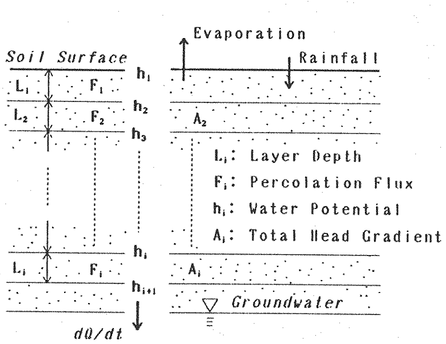

Fig. 7 Various parameters

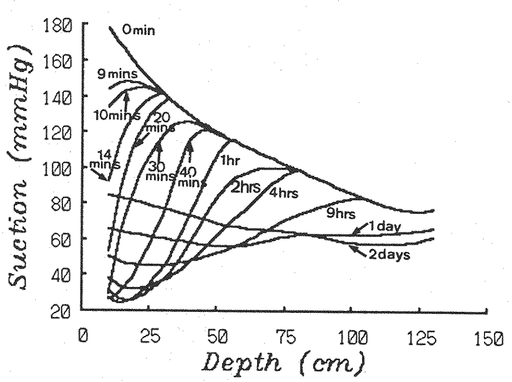

Fig. 8 Time dependence of the vertical (Within a day since a rainfall)

To know the time-dependent flow direction of pore-water, one must know the time variation of total head gradient A_i. Figure 9 shows the time variations of A_i at several locations. The plus A_i value means that the flow direction was downwards, and the minus value indicates that it was upwards. The plus peaks, whether sharp or blunt, appeared around the time when the high moisture content portion (low water potential portion) passed each location. Only in two layers shallower than 50cm did the flow direction change from downwards to upwards, after the high moisture content portion had passed. In other regions, pore-water always flowed downwards throughout a week, even if the moisture content itself decreased partly during that time. This behavior, of course, depended on the soil surface condition, such as porosity, vegetation, degree of aggregation due to fertilization or plowing, and so on (8).

Figure 10 shows the appearance time of the maximum A_i value, A_{imax}, and that of the minimum h_i value, h_{imin}, at the particular layers. The location of each layer was represented by its middle depth. The broken and dotted lines were drawn by a linear approximation. This figure shows that A_{imax} came earlier than h_{imin}. Even though h_i is the same at a particular point, $(h_{i+1} - h_i)L_i^{-1}$ has a plus value when the front portion of the moisture content profile is passing there, and a minus value when the back portion of the profile traverses the point. Therefore, A_i there becomes larger at the former case than at the latter case, even if h_i and k_i are the same. We can say the same thing as to the pore-water flux F_i as well, which means that, at every depth, the maximum flux appeared just before the highest moisture developed there. These facts remind us the hysteresis dependence of a river discharge on its depth during a flood.

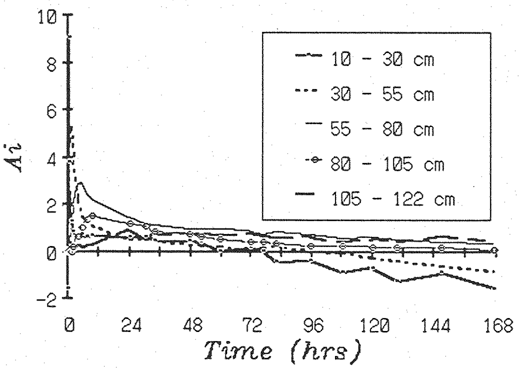

Fig. 9 Time dependence of the total head gradients at several depths (For one week after a rainfall)

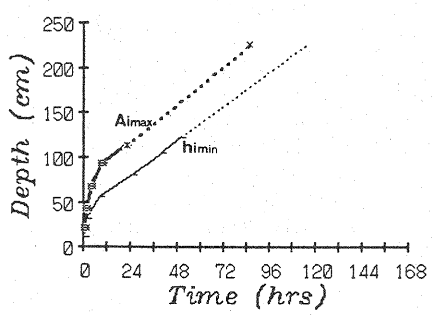

Fig. 10 Appearance times of A_{imax} and h_{imin} at the particular positions

Figure 11 shows the time variation of percolation flux dQ/dt at the bottom, which was given by the difference calculation of Q(t) data. The maximum value of dQ/dt appears at around 65 hours after a rainfall. The time when A_{imax} is detected to appear at the bottom is around 72 hours after a rainfall. There is not much difference between these two values. About 70 hours after a rainfall, dQ/dt is decreasing with time, though h_{imin} appears at the bottom. These facts show that a convex shape relation of A_i versus time is maintained through layers though it becomes blunt with time, and that the percolation flux is sensitively affected by this A_i pattern.

Figure 12 shows the time when the D_2O peak passed the depth of 25cm, 50cm, 75cm, 100cm, 125cm, 150cm, and 175cm. Here, we discuss whether the behavior of this peak can be explained by the "push-out" model or not. In this model, the pore-water is pushed down by rainfalls and the moving distance within a particular period T_d is determined by the amount of percolation at the bottom. The average net velocity of pore-water within T_d, u_p is calculated as follows:

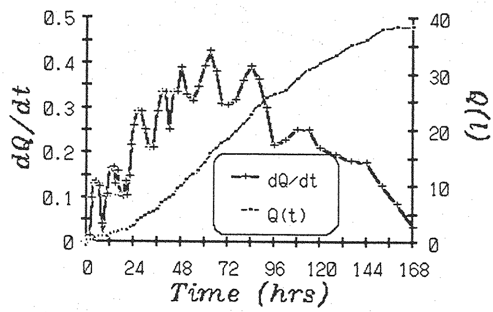

Fig. 11 Time variations of percolation flux dQ/dt and percolation amount Q at the bottom

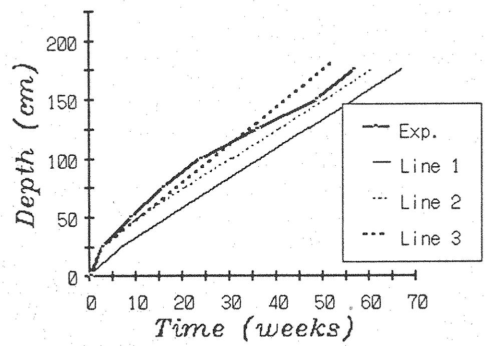

Fig. 12 Appearance time of D_2O concentration peak at seven different depths

$$u_p = Q\ T_d^{-1}\ a_L^{-1}\ (n/100)^{-1}\ (S_r/100)^{-1}\ (k_d/100)^{-1} \qquad (2)$$

where Q = the amount of percolation at the bottom in a week, a_L = area at the soil surface, n = porosity in percent, S_r = degree of saturation in percent, and k_d = draining water volume ratio (in percent) to total water volume in void. Here, Q = 371, $a_L = 2.27\times10^4 cm^2$, and T_d = 1week. Line 1 shows a weekly change of D_2O peak location $z_p(t)$, calculated where n = 73%, S_r = 65% and k_d = 100% up to 25cm deep, and n = 70%, S_r = 93%, and k_d = 100% for a depth of 25cm below.

The values of n and S_r were given based on the data of void ratio e and water content w(%) shown in Table 1. The experimental data are more than 10 weeks faster than line 1. Line 2 shows another calculated line of $z_p(t)$, given with the experimental data up to 25cm deep and calculated by Eq. 2 with n = 70%, S_r = 93% and k_d = 100% for 25cm below. Line 3 was obtained as follows: $z_p(t)$ was given by the experimental data up to 25cm deep as well as line 2, while for 25cm below, $z_p(t)$ was calculated with n = 70%, S_r = 93% and assumed value of k_d = 80%. Line 3 shows good agreement with the experimental data up to 125cm deep; however, it goes rather faster after that. For the layer from 125cm to 175cm deep, line 2 explains the experimental data better than line 3. From this discussion, the D_2O peak behavior can be estimated by the "push-out" model basically, although it is not a precise estimation. It means that the "by-pass" effect on pore-water percolation is not prevalent in the subsoil in this case.

Figure 13 shows the time when the minimum values of suction h_{min} and resistance R_{min} appeared at each measuring point. Down to a depth about 70cm, R_{min} appeared noticeably earlier than h_{min}; however, after that, there seems to be no great difference between the two times. Both data support each other in that they could surly monitor the behavior of the high moisture content formed by a rainfall and showed that the high moisture content portion was shifting through soil much faster than the actual pore-water movement.

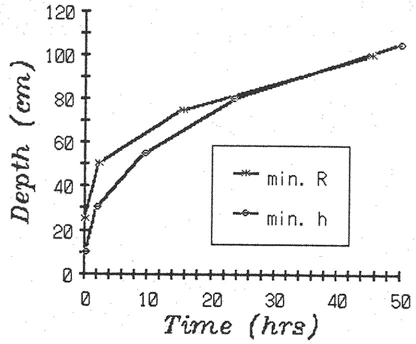

Fig. 13 Appearance time of minimum suction and that of minimum resistance for several different depths

Table 2 Comparison of moving velocity of D_2O concentration peak and that of high soil moisture peak

	Moving Velocity (cm/h)	
	Peak of D_2O Concentration (Actual movement of water)	Peak of high soil moisture (Shifting of soil moisture profile)
Topsoil	0.06	8.0 - 12.0
Subsoil	0.023	0.8 - 2.0

Table 2 shows the actual moving velocity of pore-water and the shifting velocity of the vertical profile of moisture content. The former was calculated from the D_2O peak movement result, while and the latter was calculated from the h_{min} and R_{min} shifting velocities. According to the table, the moisture content propagation is anywhere from fifty to more than a hundred times faster than the pore-water movement. This very fast propagation phenomenon may be explained as a diffusion wave or a kinematic wave behavior of pore-water.

However, the following problem must be mentioned. According to the idea by Yamada and Kobayashi (12), the propagation velocity is m times larger than that of the actual pore-water and the value of m is on the order of one. Nevertheless, the value of m obtained here was on the order of two or three. This m value is much larger than that reported by Andersen & Sevel (1), Aneblom & Persson (2), or Wilson & Gelhar (11). Although the moisture content propagation behavior can be explained basically as a kind of pressure wave, a reasonable explanation as to why the value of m obtained here is so large must be treated elsewhere.

CONCLUSIONS

The results obtained in this study may be summarized as follows:

1. The moving velocity of CL^- peak was half that of the D_2O peak in a natural soil, so Cl^- cannot be used as a tracer of moving water in natural soils containing noticeable amount of clay.
2. The actual moving velocity of pore-water was 10cm/week in the topsoil layer and about 3.5cm/week in the subsoil layer, as estimated from the moving velocity of D_2O concentration peak.
3. The D_2O peak velocity was calculated on the basis of "push-out" model. This value showed rather good agreement with the experimental value.
4. Flowing downwards, the input D_2O has spread wider vertically.
5. The change in the vertical profile of the soil moisture due to rainfall propagated much faster than the actual downward movement of the rainwater.
6. The shifting velocity of the high soil moisture peak was about 10cm/h in the topsoil layer and about 1.5cm/h in the subsoil layer.
7. This fast velocity may be explained as a traveling wave; however, the rate of this velocity to moving velocity of pore-water was much higher than those reported by other researchers ((1), (2), (11), (12) and (13)).
8. The convex moisture profile formed by a rainfall became very flat and less noticeable with time, shifting its peak location downwards; however, the percolation flux was affected sensitively by this moisture profile.

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APPENDIX - NOTATION

The following symbols are used in this paper:

a_L = area at the soil surface;

A_i = total head gradient between ith and (i+1)th layer;

A_{imax} = max value of A_i;

dQ/dt = percolation flux;

F_i = pore-waterflux from ith layer to (i+1)th layer;

h, h_i = water potential, and that in ith layer;

h_{imin} = minimum value of h_i;

h_{min} = minimum suction at each measuring point;

k_d = draining water volume ratio to total water volume in void;

k_i = unsaturated conductivity of ith layer;

L_i = thickness of ith layer;

n = porosity;

Q = amount of percolation in volume;

R = electric resistance in soil;

R_{min} = minimum value of R at each measuring point;

S_r = degreeof saturation in percent;

T_d = a period;

u_p = average net velocity of pore-water;

w = water content in percent; and

$z_p(t)$ = peak location at time t after a rainfall.