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USE OF COLD/WARM WATER AS A WATER TRACER THOROUGH SOIL IN LYSIMETER IMMEDIATELY AFTER APPLICATION

by

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ABSTRACT

To study the movement of water through soil in lysimeters immediately after an application of water, the method of cold/warm water use as a tracer was developed. The time variation of soil temperature due to cold/warm water application was measured at more than ten levels automatically. Computer controlled systems, including a timesaving data analysis system, have been developed to measure the soil temperature and other physical parameters as to percolation. The validity of our new method was confirmed and the time variations of soil temperatures at different levels enable us to discuss the lagrangian behavior of applied cold/warm water. For a quantitative discussion as to the infiltrating speed and depth of applied water from the above soil temperature data, the effect of thermal diffusion in soil on the data must be taken into account. Therefore, the thermal diffusivity of the soils has been determined from the diurnal oscillation data of the soil temperature for our future discussion.

INTRODUCTION

Desertification and soil degradation have been rapidly accelerating on a global scale. Soil erosion by water and wind and salt accumulation at the soil surface are severe problems because of the great difficulty of recovery. These problems are closely related to a severe global food shortage in the future. Practical studies to combat desertification and soil degradation, of course, are very important; however, it is indispensable to understand the mechanisms of soil desiccation and salt accumulation at the soil surface in order to provide a more effective approach to deal with these problems. Many severe salt accumulation problems caused by thoughtless irrigation without understanding the above mechanisms have been reported all over the world. We have continued experimental study of percolation using lysimeters and have reported interesting results about the actual water moving velocity and the shifting velocity of soil moisture content (Otsubo, (8)). The goal of the present study is to understand the behavior of water at topsoil layer just after its supply. For this purpose, we have developed a new procedure in which cold/warm water is used for a tracer of moving water in soils. First of all, the advantage of this tracer is discussed and an automatic measuring system of soil temperature is introduced. Secondly, the results obtained by the system are presented. Finally, a procedure to detect the thermal diffusivity of soils is introduced. This diffusivity is required to further discuss the basic infiltration/percolation patterns in topsoil, using the time variation data of soil temperature.

PROCEDURES AND SYSTEMS

To understand how the applied water infiltrates and percolates to a ground water is very important for applied studies dealing with soil pollution and salt accumulations at soil surfaces. The water applied on a surface must be followed by the lagrangian procedure. Heavy water is a relevant tracer for this purpose; however, soil solution must be sampled by a porous cup, so the available minimum sampling distance and time intervals will be about 10 cm, and about a week, respectively. It means that heavy water tracer is very useful for the study of long-term soil percolation behavior (e.g., more than several weeks). If one intends to conduct several experiments under different conditions, the heavy water applied in each experiment must not be allowed to mix in soils. Thus, one must wait until the heavy water initially applied has percolated deep enough so that the newly applied one will not mix with it. This 'waiting period' is very long for a large scale lysimeter. Therefore, we attempted to use cold/warm water as a tracer for our study of the short term behavior of applied water in topsoil layer. The advantages of cold/warm water tracer are as follows:

1) Electric thermal sensors can be buried at intervals of within 1 cm and the measuring time interval can be reduced to several seconds. Hence, the data have good spatiotemporal resolution.
2) Thermal measurement by electric thermal sensor is easy and reliable , and automatic measurement and online trend display of the experimental results are available .
3) A sensor is very cost-effective when a thermistor cable whose electrodes are connected at the end is adopted.
4) The cold/warm water reaches the ambient temperature condition within a half day, so the next experiment can be conducted with only a short wait.
5) Cold/Warm water does not pollute soils in any case whatsoever.
6) Repetition of the experiments with the same conditions is easy.
7) Soils do not have to be sampled for experiments.

Various methods have been adopted for the experiments to study the movement of water in soil immediately after an application of water and to characterize the hydraulic function of different types of macropores and pathways in percolation. Quisenberry and Phillips (14) used chloride as a tracer in their field experiments. An array of 13 tension meters was used for the measurement of time dependent water potentials at a forested mountain soil field by de Vries and Chow (3). Bouma et al. (1) used methylene blue as a tracer and adopted the morphometric techniques under a saturated flow condition. Methylene blue was also used to study the distribution of pathways in soils by Hatano et al. (4). The method of determining breakthrough curves of chloride was adopted to characterize flow patterns in saturated soils by Bouma and Wosten (2). Flourescein and pyranine were used to mark the pathways of solute movement through soils and its distribution was recorded by ultraviolet photography (Omoti and Wild (7)). Sakuma et al.(15) used water paint for a tracer to mark the pathways in soils. All methods were adopted at the fields and were useful there; however, for usage in laboratory experiments, each method has at least one disadvantage in terms of the above advantages of cold/warm water tracer method.

Experimental setup

The two lysimeters with bare soil surface, measuring 1.7 m in diameter and 2.3 in height, have been used for this study. One is called #2, another #4 here. The lysimeters kept at 20 °C are located in a green house where room temperature and humidity are controlled, but direct solar radiation is free of control. See Otsubo (8) for the soil properties packed in the lysimeters and the environments of lysimeters. The end connected thermistor cable has been adopted as a thermal sensor. A series of the sensors have been set on the soil surface and at the depths of 0.2, 2, 4, 6, 8, 10, 13, 16, 20, 25, 30, and 40 cm in the southern part of the lysimeters. To study the horizontal heterogeneity of infiltration, another series of sensors have been set on the soil surface and at the depths of 0.2, 2, 4, 6, 8, 10, 13, 16 cm each in the northern part of the lysimeter #4. The sensors of each series have not been buried on the same vertical line. Suction meters and porous cups for water sampling were buried at 0.25 m intervals from the soil surface in both lysimeters as well (Otsubo, (8)). Electric conductivity sensors have been also buried at 0.25 m intervals in the lysimeter #4. A particular amount of pure cold/warm water has been applied on the surface of the lysimeters at an appointed time every Monday morning. The temperature of cold water was about 5 °C and that of warm water was about 50 °C The time variations of soil temperature and soil electric conductivity at all the measuring points have been monitored and recorded automatically by the control of the system mentioned below. The amount of percolated water has been also monitored automatically and the suction has been read at the appointed time intervals. The water supply conditions and supplying procedures are summarized in Table 1. Each experiment was repeated four or five times under the same experimental condition to increase the reliability of the results.

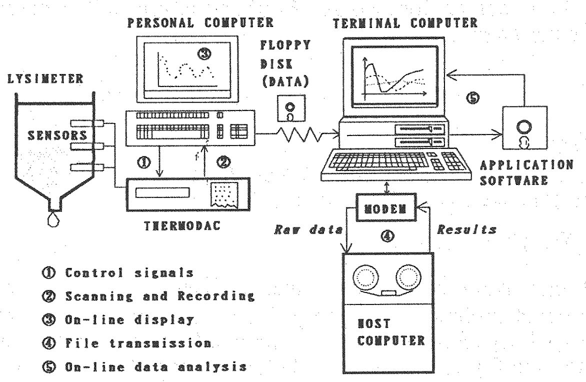
Table 1 Experimental Setup

No.	Lysi. No.	Water Temp. (℃)	G.W.L. (cm)	Qr (l) [mm]	Tr (hr)	N	Watering Procedure
1		5		130	0.05		bucket
2		22		[57.3]			wt.pot
3		5			0.05		bucket
4					1		wt.pot
5	#4	22	225	65	0.05	1	bucket
6				[28.7]	1		wt.pot
7		50			0.05		bucket
8					1		wt.pot
9	#2	5	100	65	0.05	1	wt.pot
10		22		[28.7]			wt.pot

Water temperature: Temperature of the applied water; G.W.L.: Groundwater level from the soil surface; Q_r: Amount of applied water in litters or (mm); T_r: Hours of the water application; N: Number of water applications in a week; and wt. pot: Water application by watering pot.

Systems of automatic measurement and data analysis

Figure 1 explains the systems of the automatic measurement and the data analysis developed in this study. They consist of the following three sub-systems (Otsubo & Kuboi, (10)).



Fug. 1 Schematic figure of the systems for automatic measurement and data analysis

(I) Data logger (Thermodac 32, Etoh Elec. Co. Ltd.)

This kind of apparatus is required to monitor the soil temperature and the soil electric conductivity at many points and to record them as digital data automatically day and night. Our data logger can stand alone including its internal memory; however, the measurement time interval is fixed and the data usage is limited unless the data is transferred to some other device like a floppy disk.

(II) Monitoring control by personal computer

The data logger has been controlled by a personal computer which was connected to it by the RS-232C. The developed system can scan 18 channels and save the measured data into a floppy disk within 2 or 3 seconds. The program executing the following functions was developed.

1) The measuring time interval and the number of scanning for the 18 channels have been determined in the program. For this series of experiments, the measuring time interval was one minute at the beginning of the experiments and increased with the elapsed time, as 3, 5, 10, 15, 30 minutes, and then 60 minutes as of one day after the beginning. The number of scanning time was one at first and increased with the elapsed time, as 2, 4 times and then 6 times as of one day after from the beginning. According to the number of scannings, the measured values were averaged for each channel. As to the time interval, we can convert into other values arbitrarily from the keyboard before each experiment, if necessary.
2) The averaged data at each scanning time were stored the same named file in a floppy disk during a week.
3) A real time trend graph of measured data was displayed during the idling period when data were not measured. Figure 2 shows an example of the real time trend graph of soil temperature on display. Each data from a different depth was shown in a different color on the display.

(III) Bilateral file transfer between host and personal computers.

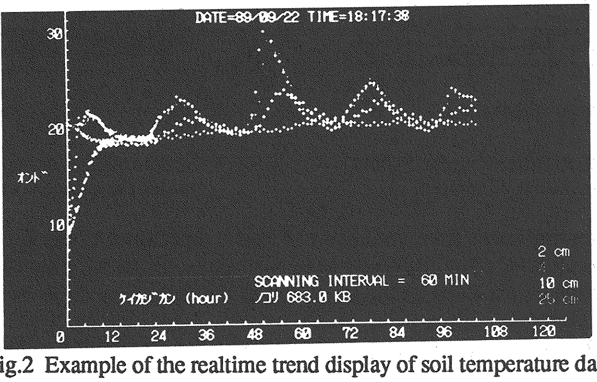


Fig.2 Example of the realtime trend display of soil temperature data

The data saved in the floppy disk as a text type file were transferred from the personal computer in the laboratory to the host computer in our institute . The amount of data was so large that the calibration of the data taken as electric signals to real physical values and the statistical analysis of the values were made by the host computer. The results were transferred reversely from the host computer to the personal one and stored on another floppy disk. Further analysis and discussion were made with the help of interactive computer graphic software.

RESULTS AND DISCUSSION

Before discussing the characteristics of infiltration from the data obtained here, we have to check the influence of cold/warm water on the infiltration and/or percolation mechanism. Philip & de Vries (13) expressed the vertical behavior of soil moisture as Eq. 1

$$\partial\theta/\partial t = \nabla\cdot(D_T\nabla T) + \nabla\cdot(D_s\nabla\theta) + \partial K/\partial z \qquad (1)$$

in which θ = volumetric moisture content; t = time; z = vertical ordinate, positive upward; T = soil temperature; D_T = thermal moisture diffusivity; D_s = iso-thermal moisture diffusivity; and K = unsaturated conductivity. They mentioned that the thermal high soil moisture environment, comparing with the order of each term in Eq. 1. Figure 3 shows the differences of the early stage time variations of suction at the lysimeter #4 caused by the different temperature of applied water under the condition of Q_r = 130 l and T_r = 0.05 h (Q_r = amount of applied water, T_r = duration time of water supply). On the other hand, Fig. 4 compares the time variations of suction of five weeks at the lysimeter #4 under the same water supply conditions, that is, Q_r = 130 l, T_r = 0.05 h, and water temperature at 5 °C. In spite of the same water supply condition, the results show scattering. The scatter of the data in Fig. 3 is not so different from that in Fig. 4. The same was recognized in the case of Q_r = 65 l (Otsubo & Kuboi, (9)). The soil moisture condition of the lysimeter #4 was always high during the experiment; the values of volumetric moisture content and the saturating index were about 0.63 and 75 % just before the watering, against about 0.72 and 96% just after the watering, respectively. That is why the results of Fig. 3 show good agreement with the findings of Philip & de Vries (13). From this discussion, we have concluded that the applied water temperature did not affect very much the percolation process at a depth of more than 10 cm under our experimental environments. The submerged state by the 50 °C water disappeared a bit earlier than that by the 5 °C water probably because of the lower viscosity of the higher temperature water. However, it did not seem beyond the scope of our study to investigate the basic characteristics of the actual water movement, the soil moisture shifting, and the pattern of applied water infiltration.

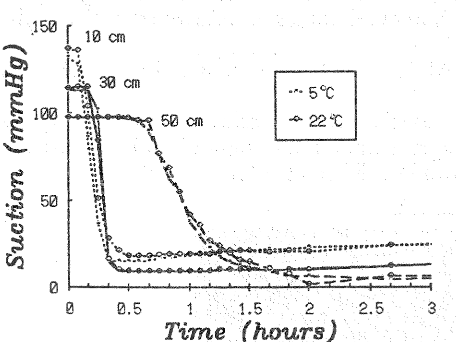


Fig. 3 Effects of temperature of applied water on the time variation of suction.

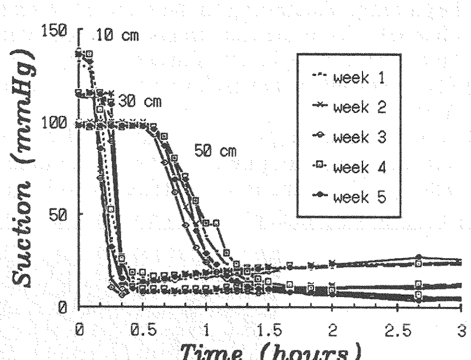


Fig. 4 Scatter of time dependent suction data under the same experimental condition.

Figure 5 shows examples of time variations of soil temperature at the lysimeter #4 in the case of water supply of 130 l with 5 °C (Fig. 5(a)) and in that of 65 l with 50 °C (Fig. 5(b)). The time variation of soil temperature at each depth includes the influence of the following three factors.

1) reaching cold/warm water
2) thermal conduction from the upper layer cooled/heated by the cold/warm water
3) diurnal thermal oscillation caused by meteorological environment.

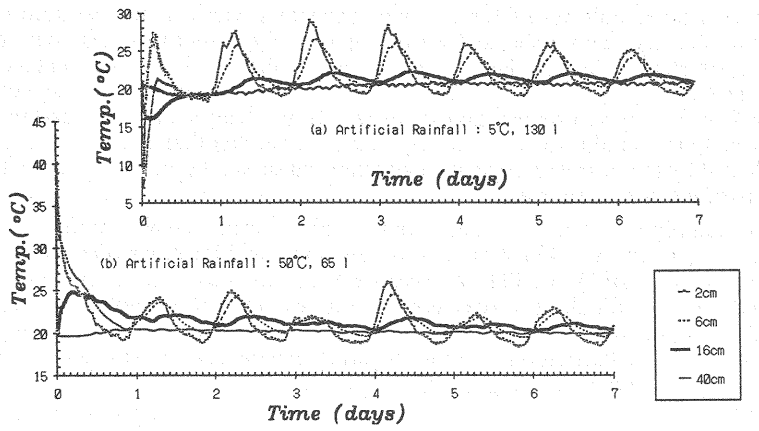


Fig. 5 Examples of time variation data of soil temperature at different depths.

The two figures of Fig. 5 suggest the following. Cold/warm water can be distinguished as a tracer until at most a quarter day from the application. The soil surface shows that the diurnal thermal oscillation caused by heat flux of the direct solar radiation and its oscillation propagates from the soil surface to the ground, damping with depth. The soil temperature at 40 cm deep is stable at 20 °C throughout a week, being affected by neither applied cold/warm water nor the diurnal oscillation at the soil surface. From the above results, the procedure using cold/warm water as a tracer of water movement in soils is available for the layer at most 30 cm deep and for the elapsed time of at most 3 hours from the application of the tracer. This condition is sufficient for our purposes mentioned above.

Figure 6 (a) shows the time variations of soil temperature at different depths, from the beginning of the water supply to six hours later, as measured by the sensors buried in the southern part of the lysimeter #4. Figure 6 (b) shows the results obtained at the lysimeter #2. The amounts of water supply were both 65 l. The response at the layer within 13 cm deep to the cold water is much earlier in the lysimeter #2 than in the lysimeter #4.

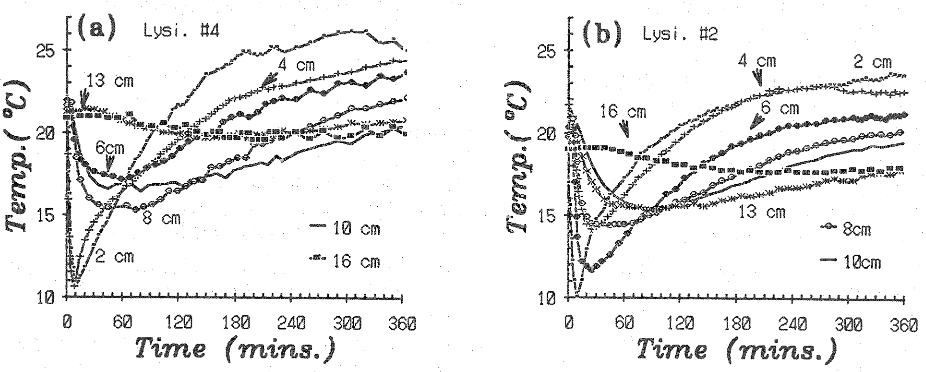


Fig. 6 Time variations of soil temperature immediately after cold water application.

The same results were obtained in the case of warm water supply. The decrease/increase of temperature at those layers due to cold/warm water was more evident in lysimeter #2 than in lysimeter #4. This suggests that the applied water percolated deeper in lysimeter #2 than lysimeter #4 and is probably because the void ratio of the former topsoil has been higher at about 3.0 than that of the latter at about 2.67, and the former topsoil is softer than the latter, so water can infiltrate/percolate more smoothly through the former one. This idea was supported by the data of saturating index at the soil surfaces of the lysimeters. The value of saturating index at ten minutes after water application was 68 % in lysimeter #2 and 96 % in lysimeter #4 under the same water application condition at 65 l (28.6 mm). As the applied water was distributed wider vertically in lysimeter #2, the saturated index was lower at the topsoil in lysimeter #2.

The common noticeable result for the two lysimeters was that temperature of some layers decreased/increased, responding to the cold/warm water supply, earlier than just their upper layer. For instance, at the lysimeter #4, the 4 cm layer responded earlier than the 2 cm layer, and the 8 cm layer did so earlier than the 6 cm layer. When 130 l was applied, the 16 cm layer also showed a quicker response than the 13 cm as well as the above mentioned layers. At lysimeter #2, the temperature decreased at 6 cm earlier than at 4 cm and, the 13 cm layer responded a bit earlier than the 10 cm layer. These facts cannot be explained by the theory of thermal conduction and should be attributed to the difference in the infiltrating depth of the cold/warm water.

Two figures in Fig. 7 compare the time variations of soil temperature obtained at the same depths of 4 cm, 6 cm, 8 cm, 10 cm, and 13 cm but at different horizontal locations (the southern and northern parts) under the condition of Qr = 130 l. A considerable difference is recognized at every pair of the same depth; however, a particular side does not seem to respond always more quickly. The results of Fig. 6 and Fig. 7 suggest that infiltration of applied water is heterogeneous in the topsoil. The soil surface was submerged at the watering, so the fingering phenomenon mentioned by Philip (11), (12) and Hino et al.(5) might have cause irregular infiltration. The by-path effect due to heterogeneity of soil might have cause it as well.

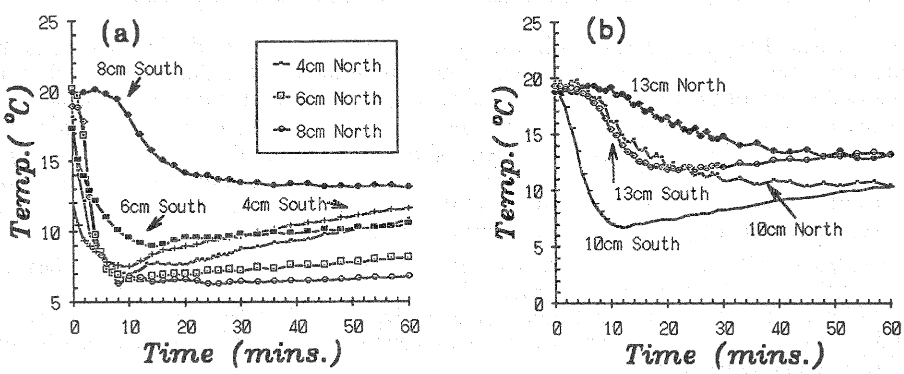


Fig. 7 Different time variations of soil temperature immediately after cold water application due to horizontal location.

The following method has been considered to estimate the infiltrating depth of the applied water from the data of the time variation of soil temperature. Supposing that the time variation of soil temperature at the depth of $z = z_t$ is given and that the cold/warm water does not infiltrate deeper than z_t, the time variations of soil temperature at depths below zt must be induced by only the above factors of 2) and 3) (i.e., thermal conduction), so they must be estimated by the equation of thermal diffusion. On the other hand, if they can not be detected, that is the experimental data show a quicker and larger response than the estimated values, the cold/warm water is concluded to have infiltrated deeper than z_t.

To apply the above method, the value of soil thermal diffusivity k must be given in advance. The values of k for the small soil samples have been determined by Kasubuchi (6). We have developed a new method to detect this value from the time variation data of soil temperature (Otsubo and Kuboi (9)). In both figures of Fig. 5, soil temperature for each depth shows a diurnal oscillation as of one day after the cold/warm water supply, and the phase delay and the amplitude damping increases with the increase of the depth. Our method is based on this phase delay and amplitude damping with depth and the following analytical solution at $t \to \infty$ of the equation by thermal diffusivity in soils.

One-dimensional thermal diffusion in soils is described as follows:

$$\partial T/\partial t = k(\partial^2 T/\partial z^2) \qquad (t > 0, -\infty < z < z_0) \qquad (2)$$

$$T = g(z) \qquad (t \to 0) \qquad \text{initial condition} \qquad (3)$$

$$T = f(t) \qquad (z \to z_0) \qquad \text{boundary condition} \qquad (4)$$

in which, T = soil temperature, and t = time and with 0 when the water is applied. The value of k usually depends on θ and void ratio e.

Considering a diurnal oscillation for the boundary condition, we approximated it with the following sinusoidal function with angular frequency ω (1/h),

$$T = A\cos(\omega t - \varepsilon) \qquad (z \rightarrow z_0) \qquad (5)$$

in which A = amplitude of diurnal oscillation of soil temperature at the depth of z_0, and ε = initial phase of T. If k is approximated as constant vertically, the analytical solution of Eq. 2 for $t \rightarrow \infty$ is given as follows:

$$T = A\, exp\,(z\sqrt{\omega/2k}\,)\cos(\omega t + z\sqrt{\omega/2k} - \varepsilon) \qquad (6)$$

The term of $exp\,(z\sqrt{\omega/2k}\,)$means the damping rate of diurnal oscillation of soil temperature and the term of $-z\sqrt{\omega/2k}$ means its phase delay at a particular depth of z from z_0. The analytical solution given by Eq. 6 shows that the phase delay and the damping rate depend on only the values of k and ω when the boundary condition is given by Eq. 5. This result indicates that if the phase delay and the damping rate are determined, the approximated value of k is detected reversely for a given ω.

At each depth where the sensor has been buried, the value of phase delay ωT_d (T_d = phase delay in hours) was examined for the data of many weeks and the average value of T_d was calculated for each depth. Table 2 shows the values of k calculated backwards from the value of T_d at several depths in the lysimeter #4 with the assumed value of $\omega = 2\pi/24$ (1/h). The value of k in the lysimeter #4 can be considered as constant at 9 cm^2/h through the topsoil. The damping rate at each depth was also examined for the same data and the results were averaged. Table 3 shows the averaged experimental values of damping rate at several depths and the calculated values for given k at 8 to 20 cm^2/h. As to the damping rate, the value of 12.5 cm^2/h for k shows the best correspondence between experimental and calculated values. For the assumed values of specific heat of soil C_p at 0.4 cal/g/°C, soil bulk density ρ_s at 1.3 g/cm^3, and k was 10 cm^2/h, the thermal conductivity $\lambda(= kC_p\rho_s)$ became 0.0013 cal/cm/s/°C. This detected value can be practical for our purpose, showing rather good agreement with the value measured by Kasubuchi(6).

Table 2 Values of soil thermal diffusivity calculated inversely from the phase delay time data.

z (cm)	4	8	14	18
Td (hr)	1.89	3.83	6.54	8.51
k(cm^2/h)	8.58	8.30	8.69	8.54
λ	0.0012	0.0012	0.0012	0.0012

λ : cal/cm/s/°C

Table 3 Comparison with experimental and calculated values of damping rate.

Damping Ratio of the Amplitude of Daily Oscillation of Soil Temperature						
z	Exp.	Calculated value for given k (cm^2/h)				
(cm)	Value	8.53	10.0	12.5	15.0	20.0
4	0.629	0.609	0.633	0.664	0.688	0.723
8	0.520	0.371	0.400	0.473	0.500	0.523
14	0.239	0.176	0.201	0.239	0.270	0.322
18	0.196	0.107	0.127	0.158	0.186	0.233

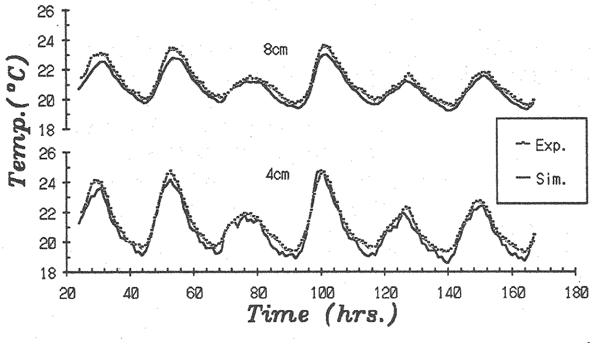


Fig. 8 Comparison of experimental diurnal oscillations of soil temperature with simulated ones for the detected value of soil thermal diffusivity.

Figure 8 shows the calculated time variation of soil temperature at 4 cm deep and 8 cm deep from one day after the water supply till seven days after the supply, in which the value of k = 10 cm^2/h was assumed and the experimental data at 2 cm were used for the boundary condition. The experimental data of soil temperature at 4 cm and 8 cm deep are also shown in Figure 8.

Figure 9 shows the measured time variation of soil temperature at 16 cm deep and the calculated ones for given k values at 10 and 20 cm^2/h to examine the effect of thermal diffusivity of soil on the calculated results. In this calculation, the same boundary condition as in Fig. 8 was adopted. The calculated time variation for k = 20 cm^2/h becomes too large in amplitude and too early compared with the measured data. From the results of Fig. 8 and Fig. 9, the time variation of soil temperature in the lysimeter #4 due to thermal conduction can be estimated, if the value of 10 to 12.5 cm^2/h is adopted for k. With the same method as above, the value of k for the lysimeter #2 was detected to be 7.5 cm^2/h.

Of course, strictly speaking, the value of k depends on soil temperature and moisture content and may have a vertical profile due to them. In fact, a moisture content detector based on the correlation between moisture content and thermal conductivity has been proposed. However, the estimated value of k here is available for our purpose, such as to detect the approximate depth and speed of infiltration due to water supply and to study its typical behavior.

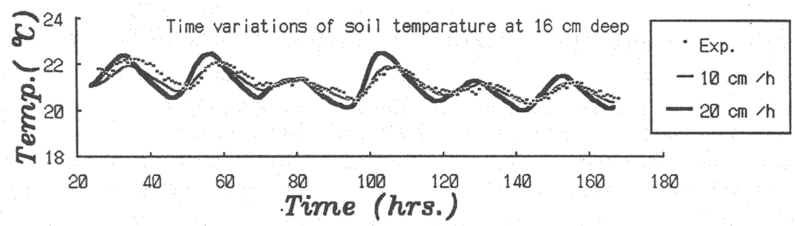


Fig. 9 Dependence of calculated time variations of soil temperature on soil thermal diffusivity.

The reason why the value of k for lysimeter #2 is smaller than that for lysimeter #4 is discussed here. The thermal conductivity of unsaturated soil is believed to decrease with the increase of void ratio in soil and to decrease/increase with the increase of air/moisture content for the same soil. As mentioned before, the void ratio of lysimeter #2 is larger than that of lysimeter #4. In terms of air content in topsoil, it increased gradually with the elapsed time from the water application in the both lysimeters. However, the volumetric air content per unit volume was always larger in lysimeter #2 than #4. For instance, on the Wednesday morning, that value was 55 % in lysimeter #2 and 33.5 % in lysimeter #4. As the topsoil of lysimeter #2 had a larger void ratio and always contained more air in it than that of lysimeter #4, the thermal conductivity for the former topsoil was smaller than that for the latter one.

The detected k values were adopted for our quantitative estimation of the infiltrating depth and speed of applied water immediately after its application. The results will be reported elsewhere soon.

CONCLUSION

The results and achievement in this study may be summarized as follows:

1. An automatic monitoring system of physical parameters on infiltration and percolation and a real time display system of monitored data, which were controlled by a personal computer, were established, and a systematic data analysis procedure was developed.
2. Cold/warm water is very much available for the tracer to study the infiltration through a topsoil less than 30 cm deep at the time stage of 2 or 3 hours after a water supply.
3. The measured time variations of soil temperature suggest heterogeneous characteristics in infiltration through a topsoil.
4. Thermal diffusivity at the lysimeters was detected to be 7.5 cm2/h for lysimeter #2 and 10 to 12.5 cm2/h for lysimeter #4 from the data of vertical transmitted properties of diurnal oscillation of soil temperature.

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APPENDIX - NOTATION

The following symbols are used in this paper.

A = amplitude of diural oscillation of soil temperatures at the depth of z_0;

C_p = specific heat of soil;

D_s = iso-thermal moisture diffusivity;

D_T = thermal moisture diffusivity;

e = void ratio of soil;

$f(t)$ = boundary condition of Eq. 2;

$g(z)$ = initial condition of Eq. 2;

K = unsaturated conductivity;

k = soil thermal diffusivity;
N = number of water application in a week;
Q_r = amount of applied water;
T = soil temperature;
t = time;
T_d = phase delay in hours;
Tr = hours of the water application;
z = vertical ordinate, positive upward;
z_0 = depth of boundary condition;
z_t = particular depth;
ε = initial phase of T;
θ = volumetric moisture content;
λ = thermal conductivity of soil;
ρ_s = soil bulk density; and
ω = angular frequency of sinusoidal function in Eq. 5.

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