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Estimation of Wet Bulb Formation in Various Soil During Drip Irrigation

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Small water resources can be utilized more effectively in the drip irrigation system. To use limited water effectively, it is important to irrigate exactly in the root zone. First, hydraulic conductivities and diffusivities on various soil types were studied. The experiment was performed on sand (Coastal sand), sandy loam (Masa), loam (Kuroboku, volcanic ash) and clay (Coral clay). Second, cylindrical compartment model to estimate wet bulb size was proposed. Wet bulb formations on various soils were studied with changing the irrigation intensity. Sand soil typically showed vertical elongation and light clay soil showed horizontal elongation. Loam (Kuroboku) and sandy loam (Masa) showed spherical elongations. Sandy loam (Masa) showed slightly vertical elongated shapes than Loam (Kuroboku). Third, the sizes of wetted area on the soil surface and of vertical depth were determine on specified irrigation intensities.

INTRODUCTION

Drip irrigation has been developed in arid countries to irrigate only root zone to save water. Obviously, drip irrigation requires less water than other irrigation methods as water consumption of the fields are minimized. It requires roughly half the water needed by sprinkler or surface irrigation. Water losses during the drip irrigation are soil surface evaporation from the partial wetting area on the soil surface and excess extension of wetted zone in the vertical direction. Up to date, however, there have been few research studies on these subjects. The factors affect on the formation of wet bulb are considered to be soil water characteristics, crop absorption by root system, soil surface evaporation and the intensity of irrigation rate. And these factors are affected by solar radiation, air temperature, air humidity, crop growing condition and so on. Various trials were conducted for clarifying the factors affecting wet bulb formation.

Studies on drip irrigation system were conducted by Nielsen (1972), Nakayama and Bucks (1986) and Richard (1989). Evapotranspiration of isolated crop was studied by Nakano *et al.* (1995). It is interesting to note, evaporation from small spot wetted area was studied by Yuge *et al.*, (2005) taking into account the small scale advection on the soil surface.

In this study, the estimation of wet bulb formation were performed applying simulation model on the on various types of soils such as coarse sand (Coastal sand), sandy loam (Masa), loam (Kuroboku, volcanic ash) and clay (Coral clay).

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HYDRAULIC CONDUCTIVITIES AND DIFFUSIVITIES

One step method

One–step method was used for determining the hydraulic conductivities and diffusivities on various types of soils. This method is based on measuring the falling rate of drainage from a sample on the tension–plate device.

$$D(\theta) = \frac{4L^2}{\pi^2(\theta - \theta_f)} \frac{\partial \theta}{\partial t} \qquad (1)$$

where D is diffusivity, L is the length of the sample, θ is instantaneous volume water content, θ_f is the final equilibrium volume water content.

When the diffusivity at the specific water content and the water content versus suction relationship are given, the hydraulic conductivity is calculated from the equation,

$$K(\theta) = -D(\theta) \frac{d\theta}{d\Psi} \qquad (2)$$

where K is hydraulic conductivity, Ψ is the suction, $d\theta / d\Psi$ is the slope of the water content versus suction relationship at water content represented by D (Doering, 1965).

Soil samples are coarse sand (Coastal sand), sandy loam (Masa), loam (Kuroboku, volcanic ash soil) and light clay (Coral clay). This method is limited to the soil water suction less than about 1000 hPa.

Hydraulic conductivities and diffusivities on various soil

Soil water diffusivity and hydraulic conductivity obtained by the one–step method, on coarse sand, sandy loam, loam and clay are shown in **Figs. 1**, **2**, **3** and **4**, respectively.

Diffusivities and hydraulic conductivities of each soil

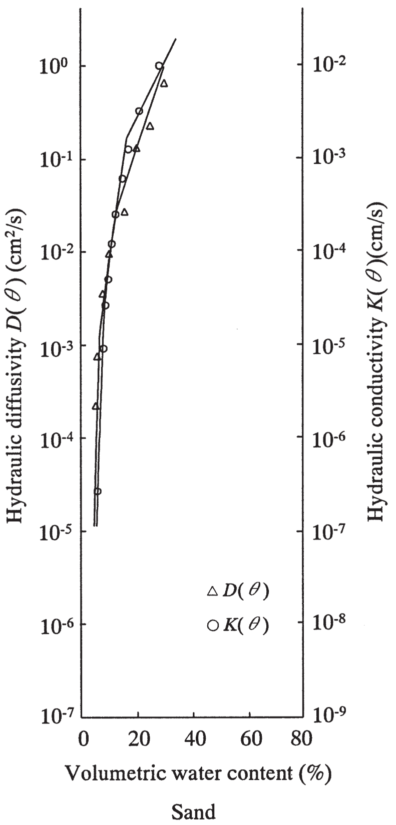


Fig. 1. Hydraulic conductivity and diffusivity of Sand (Coastal sand).

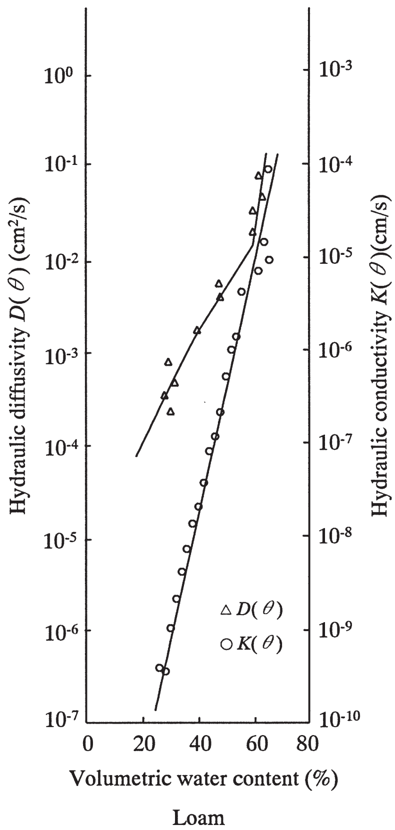


Fig. 3. Hydraulic conductivity and diffusivity of Loam (Kuroboku).

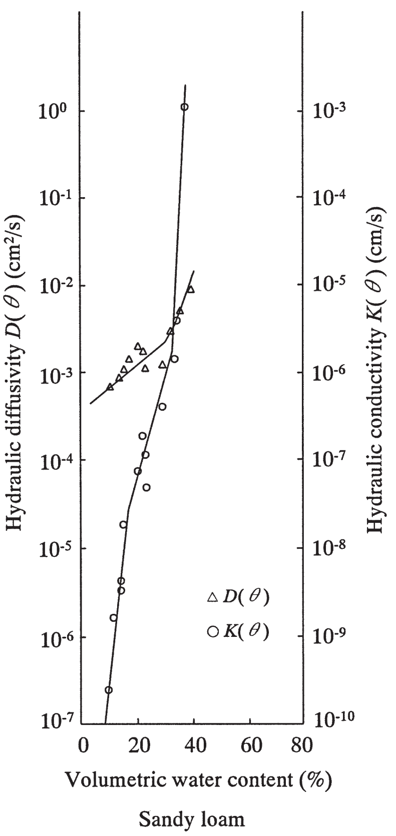


Fig. 2. Hydraulic conductivity and diffusivity of Sandy loam (Masa).

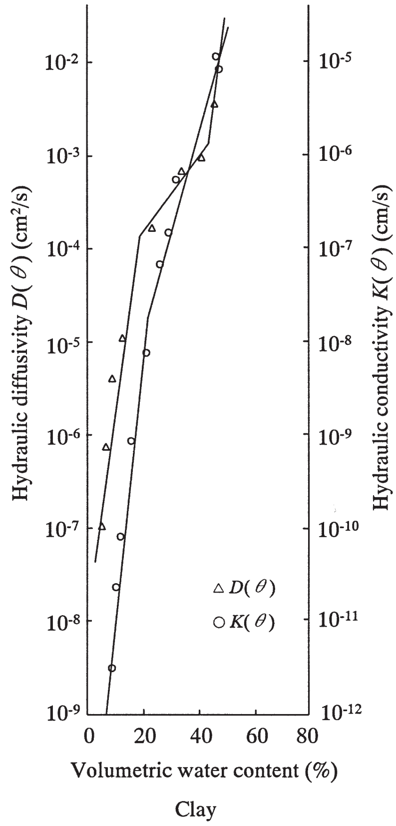


Fig. 4. Hydraulic conductivity and diffusivity of Clay (Coral clay).

are expressed by equations with powers as follows.

(1)Sand (Coastal sand)

Diffusivities

$$D(\theta)=3.70\times10^{101\theta-5.0} \quad 0.054<\theta<0.067$$
$$D(\theta)=3.36\times10^{22.3\theta} \quad 0.067<\theta<0.127 \quad (3)$$
$$D(\theta)=1.59\times10^{9.12\theta-2.0} \quad 0.127<\theta<0.34$$

Conductivities

$$K(\theta)=1.66\times10^{70\theta-6.0} \quad 0.054<\theta<0.091$$
$$K(\theta)=5.01\times10^{20.8\theta-2.0} \quad 0.091<\theta<0.167 \quad (4)$$
$$K(\theta)=1.45\times10^{6.07\theta+1.0} \quad 0.167<\theta<0.34$$

(2) Sandy loam (Masa)

Diffusivities

$$D(\theta)=3.70\times10^{2.64\theta-4.0} \quad 0.088<\theta<0.030$$
$$D(\theta)=2.75\times10^{6.40\theta-5.0} \quad 0.30<\theta<0.38 \quad (5)$$

Conductivities

$$K(\theta)=2.18\times10^{30.35\theta-13.0} \quad 0.088<\theta<0.167$$
$$K(\theta)=2.47\times10^{11.96\theta-10.0} \quad 0.167<\theta<0.325 \quad (6)$$
$$K(\theta)=1.51\times10^{68.0\theta+28.0} \quad 0.325<\theta<0.38$$

(3) Loam (Kuroboku, volcanic ash)

Diffusivities

$$D(\theta)=7.06\times10^{5.96\theta-6.0} \quad 0.2<\theta<0.4$$
$$D(\theta)=2.22\times10^{4.72\theta-5.0} \quad 0.4<\theta<0.6 \quad (7)$$
$$D(\theta)=1.38\times10^{18.4\theta-13.0} \quad 0.6<\theta<0.7$$

Conductivity

$$K(\theta)=3.0\times10^{12.3\theta-6.0} \quad 0.2<\theta<0.7 \quad (8)$$

(4) Light Clay (Coral clay)

Diffusivities

$$D(\theta)=8.97\times10^{20.76\theta-9.0} \quad 0.075<\theta<0.202$$
$$D(\theta)=2.32\times10^{3.86\theta-5.0} \quad 0.202<\theta<0.457 \quad (9)$$
$$D(\theta)=4.39\times10^{22.95\theta-13.0} \quad 0.457<\theta<0.50$$

Conductivities

$$K(\theta)=1.23\times10^{27.01\theta-14.0} \quad 0.075<\theta<0.23$$
$$K(\theta)=7.98\times10^{10.43\theta-11.0} \quad 0.23<\theta<0.50 \quad (10)$$

CALCULATION OF SOIL WATER FLOWS

Three dimensional soil water flows can be expressed by following equation,

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}[D(\theta)\frac{\partial\theta}{\partial x}]+\frac{\partial}{\partial y}[D(\theta)\frac{\partial\theta}{\partial y}]+\frac{\partial}{\partial z}[D(\theta)\frac{\partial\theta}{\partial z}]-\frac{\partial K(\theta)}{\partial z} \quad (11)$$

where θ is volumetric soil water content, $D(\theta)$ is soil water diffusivity, $K(\theta)$ is hydraulic conductivity, t is time, x and y are horizontal distances, and z is vertical distance (Hillel. 1984,1985). Soil water movement under drip irrigation is expressed by cylindrical coordinate, as irrigated water percolate in radial direction. To treat radial soil water flow, eq. (11) is better transformed to cylindrical coordinate system as follows,

$$\frac{\partial\theta}{\partial t}=\frac{\partial\theta}{\partial r}[D(\theta)\frac{\partial\theta}{\partial r}]+\frac{D(\theta)}{r}\frac{\partial\theta}{\partial z}+\frac{\partial}{\partial z}[D(\theta)\frac{\partial\theta}{\partial z}]-\frac{\partial K(\theta)}{\partial z} \quad (12)$$

where r is radial distance (Nakano and Cho,1987).

Eq. (12) can be calculated by using compartment model. The cylinder was divided into sections as shown in **Fig. 5**. The region was expressed by a cylinder with radius 36 cm and depth 72 cm. Soil column was divided into 20 layers vertically such as 0.5 cm, 0.5 cm, 1 cm, 1 cm, 1.5 cm, 1.5 cm, 3 cm times 9, 4 cm, 5 cm, 8 cm, and 10 cm times 2. For radial direction, radius 36 cm was divided into 35 sections with 1cm radial distance. Each compartment is composed of concentric circle with radial width 1cm and specified vertical widths.

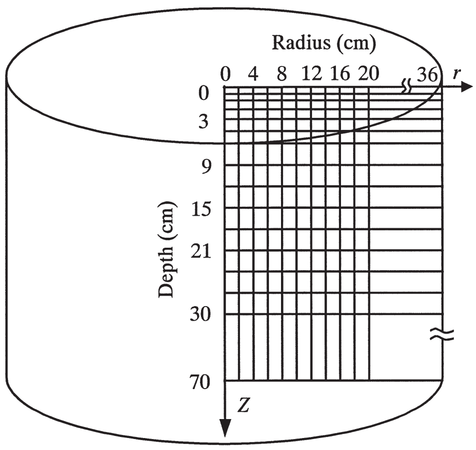


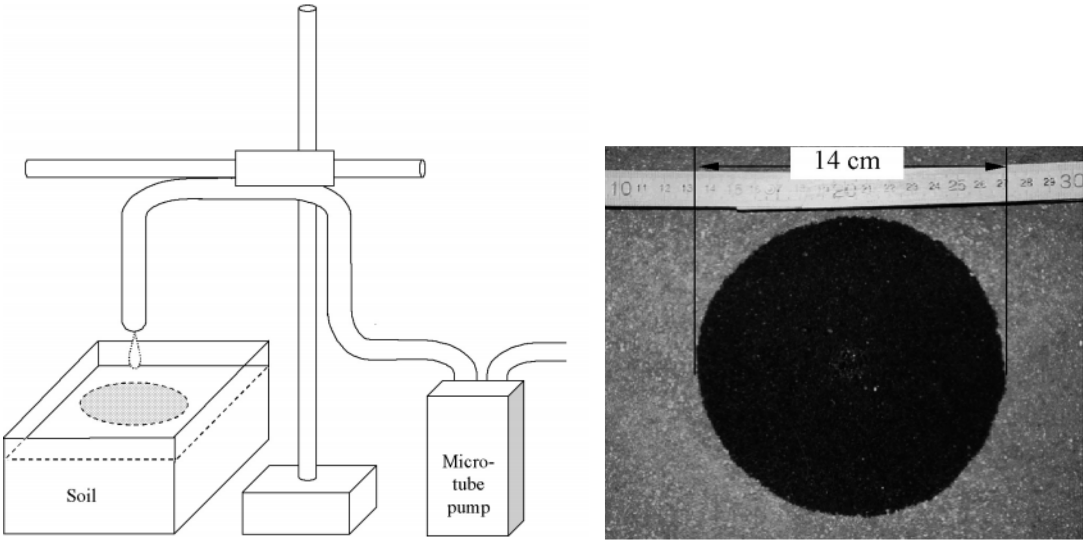
Fig. 5. Cylindrical compartment model.

WET–BULB FORMATION

Experiments on wet–bulb formation during and after drip irrigation

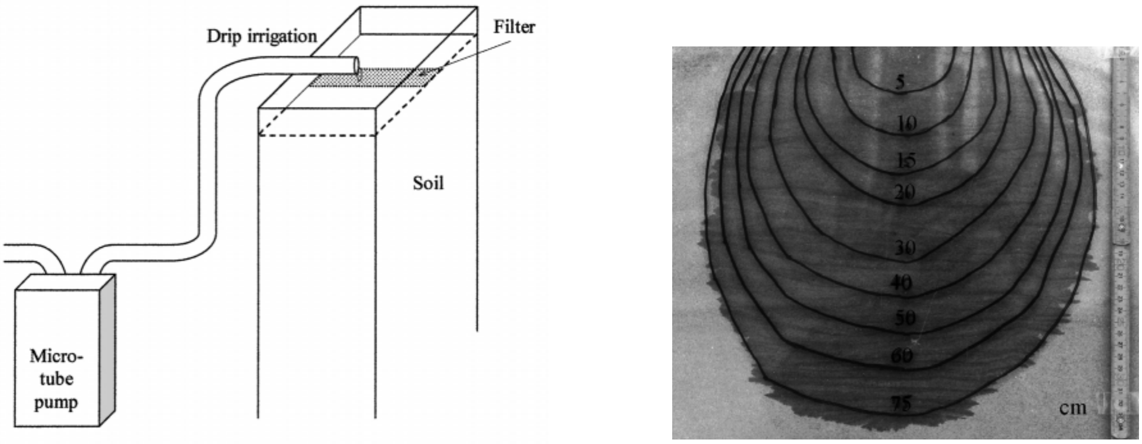
Fig. 6 shows the experiment on the formation of wetted area on the soil surface. Micro–tube pump was used to control flow rate. When irrigation water was applied to loam (Kuroboku) with intensity 0.18 litter/h, wetted circle with diameter 14 cm was formed on the soil surface after applying irrigation 90 min. Wetting front could be seen clearly at surface soil layer.

Fig. 7 shows the experiment on the formation of wetted area in the vertical section during the line source irrigation to the sand. Irrigation water was applied by micro–tube pump with flow rate 1.6 litter/h to 5 cm slit. The times of each wetting fronts were shown in the figure. Wet bulbs in each time steps show ellipsoidal shapes. The vertical depth of wetted bulb reached 33 cm after 70 min.



(a) (b)

Fig. 6. Wet bulb formation in the horizontal direction.



(a) (b)

Fig. 7. Wet bulb formation in the vertical direction.

Simulation on wet–bulb formation during and after drip irrigation

Initial condition was assumed as 1000 hPa. Drip irrigation intensities were variously changed from 0.1 to 1 litter/h on four types of soils. Total amounts of applied water were changed from 0.4 to 8 litters. Crop transpiration and soil surface evaporation were not taken into account.

Fig. 8 shows the calculated result on during and after drip irrigation on of sandy loam. The irrigation intensity of Fig. 8 (a) and (b) were specified as 0.1 and 1 litter/h, respectively. The irrigation was stopped after 4 hours. Total amounts of irrigation of Fig. 8 (a) and (b) were 0.4 and 4 litters, respectively. Equal volumetric soil water content lines were shown with 2% step from 12% to wetted condition. During irrigation, the figures show as the time lapse, wet bulb enlarged spherical shape in small irrigation intensity and in high irrigation intensity the shapes show ellipsoid with enlongated in the vertical direction. After irrigation, caused by the redistributions of water, wet bulbs were continued elongations, especially in the high irrigation intensity.

Fig. 9 shows the calculated results of volumetric water contents change of four types of soils. Initial condition was assumed as 1000 hPa. The initial volumetric water content on sand, sandy loam (Masa), loam (Kurokoku, volcanic ash) and clay (Coral clay) were 8%, 10%, 44% and 30%, respectively. Equal volumetric soil water content lines in each soil were shown four hours later after irrigation with intensity 1 litter/h. Outer lines of each wet bulb on sand, sandy loam, loam and clay were 10%, 12%, 46% and 32%, respectively. Sand soil

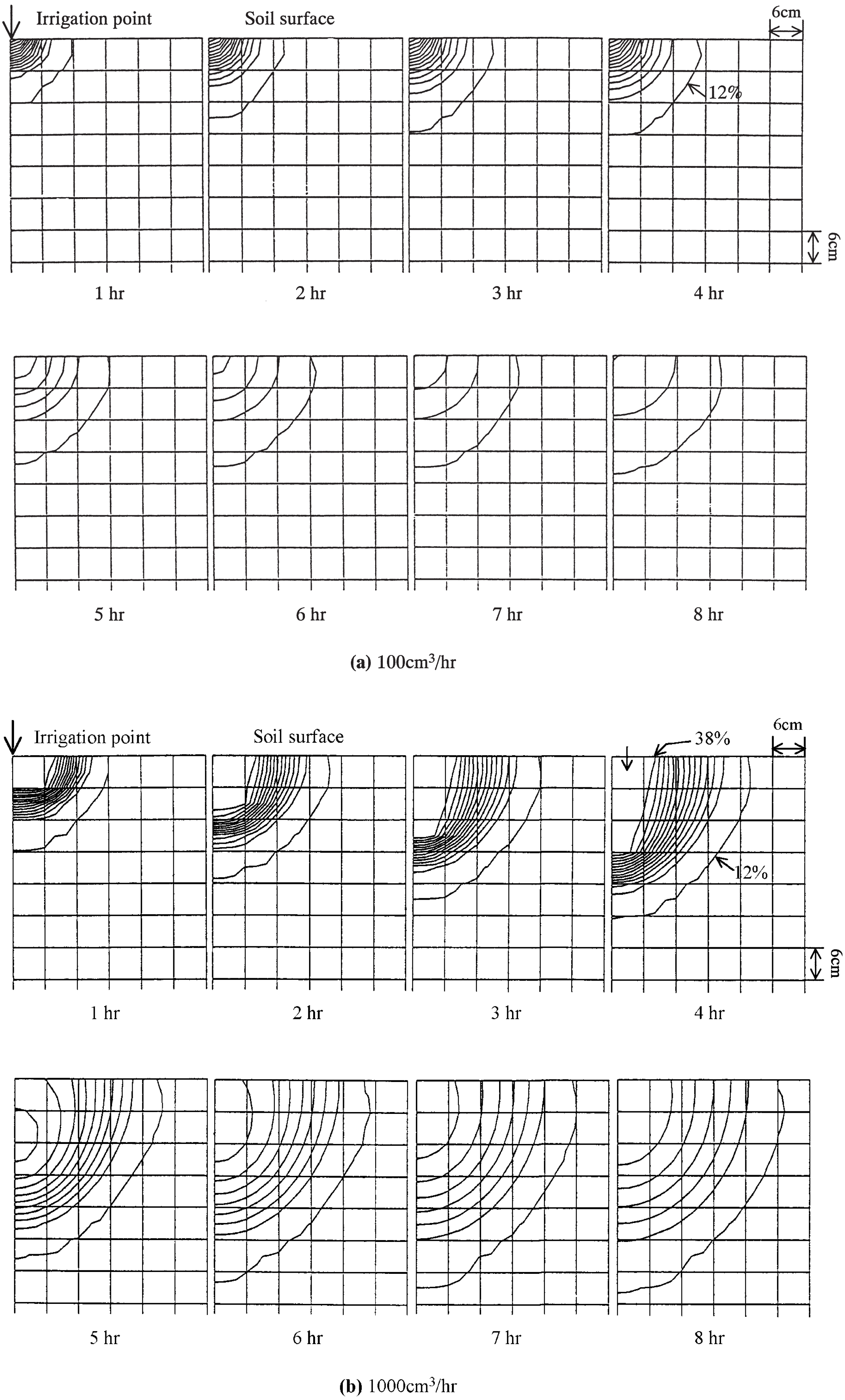


Fig. 8. Wet bulb formation in different irrigation intensities.

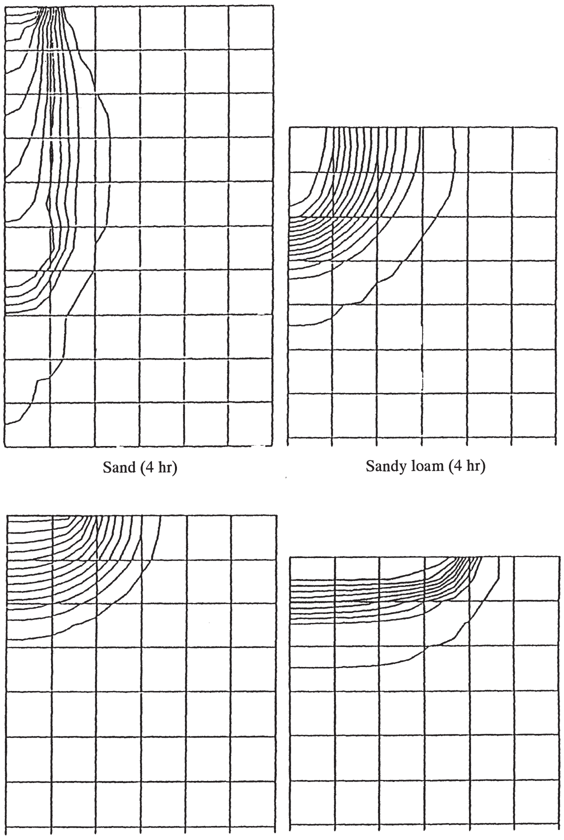


Fig. 9. Wet bulb formation in various soils.

typically showed vertical elongation and clay soil showed horizontal elongation. loam (Kuroboku) and sandy loam (Masa) showed spherical elongations. Sandy loam (Masa) showed slightly vertical elongated shapes than loam (Kuroboku).

WET–BULB SIZE ESTIMATION

Wet–bulb sizes in the horizontal direction

Fig. 10 shows the relationships between wet bulb size on the soil surface and total amount of irrigation water on four types of soils. Irrigation intensity was assumed 1 litter/h. Evapotranspiration during irrigation was assumed as zero. Soil water content at the edge of wet bulb was assumed 30 hPa. Sand soil rapidly reached to the maximum radius and showed no elongation during farther irrigation. Wet bulb on sandy loam, loam showed steady elongation. Light clay soil showed rapid elongation in the horizontal direction. As the region of area was restricted to 72 cm in the radial direction, elongation of wet bulb beyond the region was not considered.

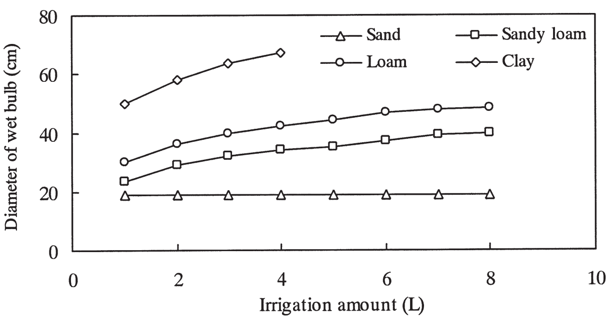


Fig. 10. Wet bulb size in the horizontal direction.

Wet–bulb sizes in the vertical direction

Fig. 11 shows the relationships between wet bulb size in the vertical direction and total amount of irrigation water on four types of soils. Irrigation intensity was assumed 1 litter/h. Evapotranspiration during irrigation was assumed as zero. Soil water content at the edge of wet bulb was assumed 30 hPa. Light clay soil, loam and sandy loam showed steady elongation. Sand soil showed rapid elongation in the vertical direction. As the region of area was restricted to 70 cm in the vertical direction, elongation of wet bulb beyond the region was not considered.

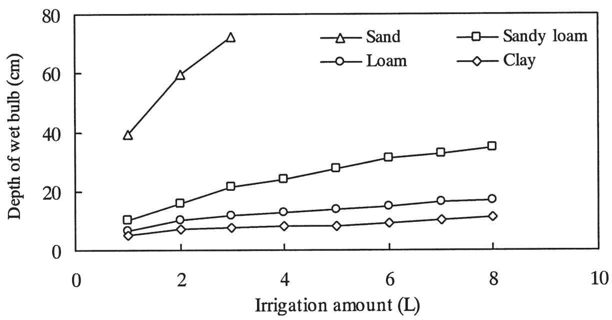


Fig. 11. Wet bulb size in the vertical direction.

CONCLUSIONS

Hydraulic conductivities and diffusivities on various soil types were studied. The experiment was performed on coarse sand (Coastal sand), sandy loam (Masa), loam (Kuroboku originated in volcanic ash) and light clay (Coral clay). Cylindrical compartment model to estimate wet bulb size was proposed. Wet bulb formations on various soils were studied with changing the irrigation intensity. Sand soil typically showed vertical elongation and light clay soil showed horizontal elongation. Loam (Kuroboku) and sandy loam (Masa) showed spherical elongations. Sandy loam (Masa) showed slightly vertical elongated shapes than Loam (Kuroboku). The sizes of wetted area on the soil surface and of vertical depth were determine on specified irrigation intensities. If irrigation intensity is specified as 1 litter/h, horizontal diameter of wetted area on the soil surface and vertical length of wet bulb versus total amount of irrigation can be estimated. If these figures are prepared on various irrigation rates, wet bulbs in each irrigation condition can be estimated. The study presented here would be effectively used for planning drip irrigation.

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