WATER DISTRIBUTION RESPONSE IN A SOIL-ROOT SYSTEM FOR SUBSURFACE PRICISION IRRIGATION

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ABSTRACT:

A subsurface capillary irrigation using a fibrous water source buried in soil has been developed as a new precision irrigation system. This system has advantages in efficient irrigation to save much water and real time measurements of soil-plant evapotranspiration. Creating this new subsurface capillary irrigation system, we require deep understanding on detail infiltration responses in the soil-root system. This paper aims to analyze the water flow in soil during infiltration process. In the experiments, the advance wetting front was formed around the water source that was captured by using a time lapse camera. The Infiltration responses were analyzed by introducing the transfer function modeling. The transfer function parameters determined form the experimental data allows the prediction of the cumulative infiltration processes.

Keywords: Precision Irrigation, Infiltration process, Soil water content, Wetting Front, Step Response

INTRODUCTION

Precession irrigation involves the accurate and precise application of water to meet the specific requirements of individual plants and minimize adverse environmental impact (Raine et al., 2007). A simple method of subsurface capillary irrigation has been developed (Ohaba et al., 2009). The subsurface irrigation is driven only by capillary water flow, and which is characterized by the precious adaptation to requirements of water by plants, the real time measurement of evapotranspiration, and non-percolation of water and nutrients, and little evaporation from soil. This method has a great potential to fulfill the water requirements to meet plant water need (Ohaba et al., 2010; Shukri et al., 2011; Li, Q. et al., 2011).

During the subsurface irrigation process, a soil wetting zone is formed above the water source. The dynamics of this water distribution is pre-requisite for the design and operation of this irrigation system. The water distribution is varied continuously to correspond to the soil properties, plant roots, and water rate of irrigation. The theoretical and experimental researches have been requested to elucidate the system dynamics during the subsurface capillary irrigation. Preceding research for subsurface irrigations can be seen as references such as

related infiltration analyses (Green and Ampt, 1911; Moltz et al, 1968; Philip 1972; Al-Jabri et al., 2002) and irrigation system practices (Bresler et al., 1971; Vellids et al., 1990; Ah Koon et al., 1990). Further studies suggest the mutual interaction between soil and water uptake by plants (Feddes et al., 1976; Malik et al., 1988). However, the irrigation techniques developed by us are different from those in conventional irrigations. Thus, further studies were plane to determine the fundamental response of the water distribution to the adaptive control of the irrigation system.

In present experimental study, we analyzed the horizontal infiltration caused by the capillary flow out from a sheet of a rectangular fibrous water source. This study was carried out for the aim to realize practical algorithm for the optimal irrigation zone control in the subsurface irrigation. The transient responses of the cumulative infiltration are reviewed to analyze the shape of water sphere and the cumulative water volume using the infiltration dynamic characteristics. The two dimensional infiltration will be analyzed using the transfer functions.

MATERIALS AND METHODS

Experimental method
The horizontal infiltration setup is shown in Fig. 1(a). The system is composed of a soil container, a water supply system, two electronic balances and a camera. The dimensions of the soil container made of clear acrylic plates are 40 cm in width, 50 cm in length, and 6 cm in depth. The water supply system consists of a water level control tank with a reservoir and a water tank underneath the soil container. Water was supplied through a sheet of a rectangular fibrous source (Toyobo, BKS0812G) which one end was buried in the soil and the other put into the water supply tank. The water potential of the fibrous source is a function of the water head $h(t)$ that is controlled the displacement of a water level by a mechatronics system using a labo-jack. A float in the water control tank enables to keep the water level at a constant value.

Figure 1 (b) illustrates the top view of the horizontal soil plane with a Cartesian coordinate system. The fibrous line source is located at the origin along the y-axis. The height of the source was 4 cm. Soil moisture sensors (Decagon, DC-5) are located at the different points P1 ($x = $ 4cm), P2 (8cm) and P3 (12cm). The matric potential of the soil was measured by the tension meters at P1 and P2. The advance wetting front was monitored by a digital camera (Brinno, Gardenwatchcam) above the soil surface. The soil surface was covered with clear acrylic plates to stop the soil evaporation. The cumulative infiltration was measured by an electronic balance (AND, GF-3000). The total water consumption was also measured by an electronic balance (AND, GX-06). The data was captured automatically by a data-logger (Graphic, GL820), and the data sampling time was 5 minute. Karma clay soil was used in the experiment. The experiment was conducted in a laboratory in Tokyo University of Agriculture and Engineering.
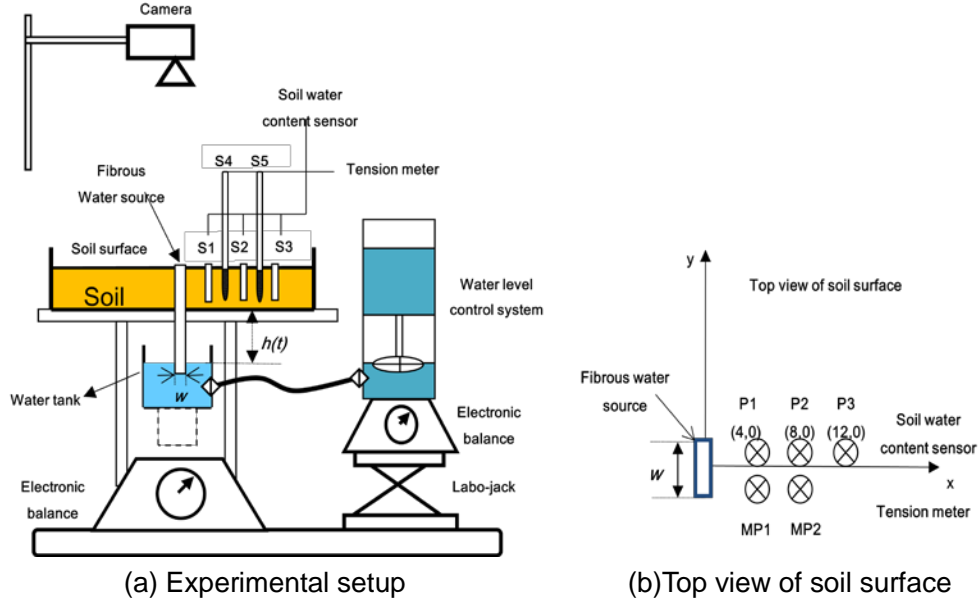
(a) Experimental setup   (b)Top view of soil surface

Fig.1. Experimental Setup for horizontal infiltration

Theoretical back ground

A well-known equation for water conservation is defined to analyze the dynamic water flow during the infiltration process. This equation is shown in Eq. (1)

$$\rho_w V \frac{d\theta}{dt} = J_{wi} - E_s - E_p \quad (1)$$

where $\theta(t)$ is the soil water content (SWC), J_{wi} is the water inflow to the soil, ρ_w is the density of water, V is the volume of water entry to the soil, E_s and E_p are the water losses from the soil system caused by the soil evaporation and the plant transpiration, which does not contain in our experiment.

For linear time invariant (LTI) systems, the transfer function models are introduced to denote dynamic responses between selected inputs and outputs of the physical system. These modeling are used extensively in the field of control system design because it is often the most effective way to incorporate LTI other elements in otherwise physical computational model (Franklin et al., 1998).

In our transfer function modeling, the first order transfer function of $G(s)$ was used:

$$G(s) = \left(\frac{K_p}{1 + \tau_p s} \right) e^{-\tau_d s} \quad (2)$$

where K_p is the gain constant, τ_p is the time constant, and τ_d is the time lag. The step response of $\theta(t)$ for the input of the water head $h(t)$ is given by:

$$\theta(t) = K_p \left(1 - e^{-\frac{t - \tau_d}{\tau_p}} \right) H(t - \tau_d) \Delta u \quad (3)$$

where $\theta(t)$ is obtained from the inverse Laplace transform using Eq. (2),

$H(t - \tau_d)$ is the Heaviside function which is equal to 1 within $t \geq t_d$ and 0 at other time, Δu is the value of the step function.

RESULTS & DISCUSSIONS

Figure 2 shows the experimental matric potential and the volumetric water content curves for the Karma clay soil. The curve has a point of inflection. In Fig. 2.the SWC gradient is changed at Ψ_m = -230 cmH$_2$O and increases from this point.
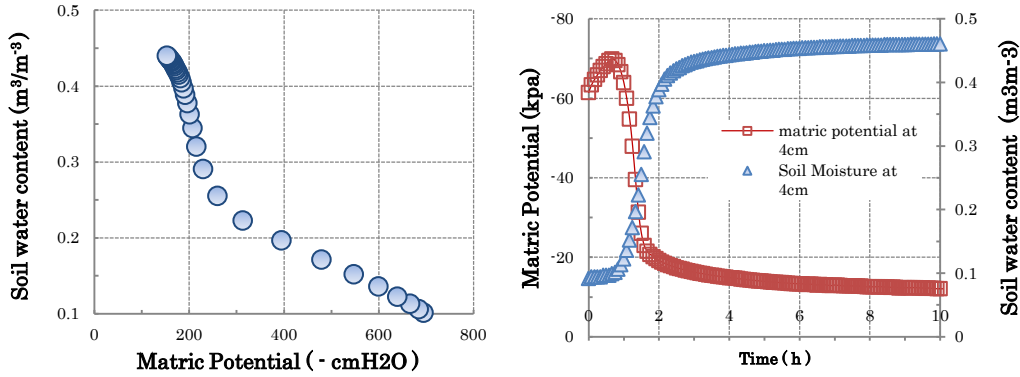

Fig.2 Soil characteristic function   Fig.3 Matric potential and soil water content

Figure 3 shows the transient response of SWC and the matric potential. As can be observed, when the infiltration starts, SWC increases from the initial value 10 % associated with the negative matric potential decrease from the maximal value -70kpa. After about 4 hours, SWC approaches to the saturated value 45%. The negative matric potential changes at about 2 hours when SWC is about 30%, and also approaches to the steady value -15kpa.

Response of soil water content
Figure 4 shows the time variation of SWC at P1, P2. We can see the typical SWC step responses in the horizontal infiltration. SWC at P1 increases from 10% at the beginning of the infiltration and approaches to the saturated value of 45%. This result suggests the first order response of infiltration. Thus we assume that the SWC responses might be determined based on transfer functions obtained from the experimental results.

Table 1. Transfer function Parameters of step responses at each point

Position	$K_p (m^3 m^{-3})$	$\tau_d (h)$	$\tau_p (h)$
P1	0.36	1.08	0.50
P2	0.36	4.10	1.25
P3	0.36	7.93	1.90

In our transfer function modeling of SWC, we estimated the unknown parameters in Eq. (2) based on the input function of $h(t)$. These parameters at each point are defined in Table.1

In Fig.4, the step response of SWC at P1 and P2, obtained by using the transfer function, is well matched with the experimental result. Thus this transfer function modeling is suitable for the prediction of SWC dynamic response.
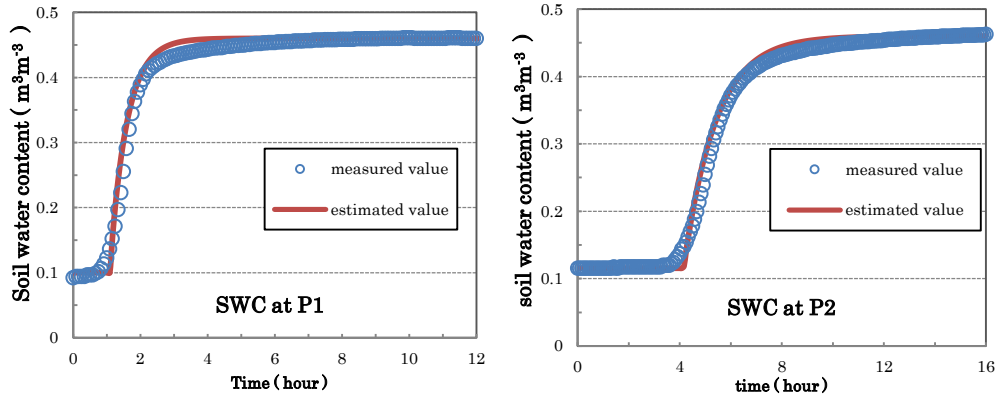

Fig.4 Step response of SWC for measured data and estimated output

Wetting front and Cumulative infiltration
Figure 5 shows the displacement of the wetting front. In the experiment, a soil water cylinder (SWC) formed around a sheet of the fibrous water source. The wetting front moves faster at first and slows down to a more constant speed at longer times. Finally, the wetting front shape does not change as it moves away from the water source. This dynamic response gives the significant information about soil water movement during the filtration.
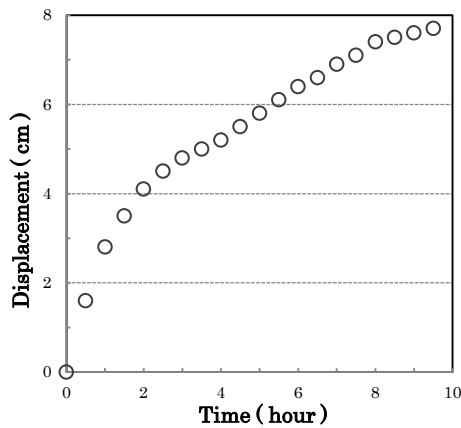

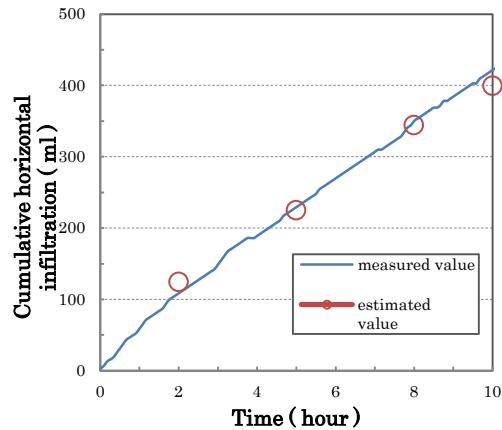Fig.5 Deformation of wetting front   Fig.6 Cumulative horizontal infiltration

Figure.6 shows the comparison of the cumulative horizontal infiltration between the measured and estimated values. The prediction of cumulative infiltration was obtained based on the finite difference method for Eq. (1) and the interpolation method for Eq. (3). We divided the time span into four regions, and we determined each region parameters in Eq. (3). During this process, the cumulative horizontal infiltration responses were estimated for each region. It can be seen

that the experiment result is almost a linear function. It is clear that the estimated values are well matched to the cumulative infiltration. This result indicates that the transfer function model is suitable for the prediction of water flow due to the infiltration. It is feasible to use this finite difference method for the prediction of cumulative infiltration.

CONCLUSIONS

This study has observed and analyzed the horizontal infiltration process. When infiltration starts, the soil water content increases associate with the soil matric potential, and approaches to a steady state values. The transfer functions of soil water content are determined, and the cumulative infiltration process is estimated by the water conservation equation and transfer function modeling. The estimated values are well matched with the experimental results. This shows the possibility to use the transfer function for the prediction of soil water response. The dynamic water flow in soil-root system will be continued based on the infiltration analysis. These data will be utilized to design of the process algorithm for the operation of the subsurface precision irrigation.

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