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Soil Water Permeability Measurement for Irrigation Scheduling on Tenggeli Desert in China

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In the arid and semi–arid areas where soil water holding capacity is small, research in the soil water characteristics such as the hydraulic conductivity, diffusivity and water retention is important for the proper irrigation scheduling to provide the sustainable and steady crop production. In this research, the permeability of the soil in Tenggeli desert was measured, and a numerical study of the infiltration process was conducted. The available moisture was 10.3% for the original desert sand. But it was proved that available moisture increased up to 27.5% in an irrigated field because of cultivation with the water supply from the Yellow river. The unsaturated hydraulic conductivity in drying process ranged from 10^{-3} to 10^{-6}cm/s for the sand soil and 10^{-5} to 10^{-8}cm/s for the top layer soil. On the other hand, that in wetting process ranged from 10^{-5} to 10^{-7}cm/s for the sand soil and 10^{-6} to 10^{-7}cm/s for the top layer soil. These data will contribute to sustainable development of agriculture at the middle reaches of the Yellow River basin.

INTRODUCTION

Crop production in the arid and semi–arid areas is very important because of the problem of population increase in China. Especially, production of upland crops such as wheat, corn and dry–field rice at middle reaches of the Yellow River basin are essential to provide the food for Chinese population. In the arid and semi–arid areas where soil water holding capacity is small, the researches in the hydraulic conductivity, diffusivity and water retention of the soil are the basic factors for the proper irrigation scheduling to provide the sustainable and steady crop production.

In this paper, in order to grasp the soil water movement that is the basic information to plan the proper irrigation scheduling at an upland field located in the middle reaches of the Yellow River, the soil permeability was measured, and a numerical study of infiltration process was conducted.

STUDY SITE

The study site was the middle reaches of the Yellow River basin, where the Tenggeli desert spreads, located at the northeast of Lanzhou city in China (E 104° 57’, N 37° 27’, Altitude 1340 m). The climate at the site was categorized as the arid region. Rainy season is from July to September and annual precipitation is a little (200 mm/year). Temperature difference between the highest and lowest in a year is large, the average temperature of the hottest month is 32 °C and the lowest is −10 °C.

METHODS AND RESULTS

For 30 years, upland crops and fruits had been grown using the Yellow River water at a field in the study site. As a result of irrigation for a long period, there was a layer of the accumulated soil in the field. The layer was composed of the desert sand, silt and clay soils carried from the Yellow River, and a thickness of the layer was about 40 cm. The soils were sampled from the surface layer, i.e. accumulation layer, and deep layer, i.e. original desert layer, in the upland field, and the soil water characteristics of them were measured.

Soil texture

Table 1 shows the results of particle size analysis. Soil texture of the deep layer soil was loamy sand (LS) and that of the surface layer soil was sandy loam (SL). A coarse sand fraction of the surface layer soil was less than one–tenth of the deep layer soil. The surface layer soil contained large percentage of fine sand and contained the silt and clay about 3 times of the deep layer soil. The reason why the surface layer soil contained much silt and clay in comparison with the deep layer soil was that the irrigation water of Yellow River contained silt and clay.

Table 1. Soil composition fraction and texture

Soil components	Deep layer soil	Surface layer soil
Coarse sand (2〜0.2 mm)	41.7%	3.8%
Fine sand (0.2〜0.02 mm)	51.7%	78.2%
Silt (0.02〜0.002 mm)	3.8%	9.0%
Clay (0.002 mm＞)	2.8%	9.0%
Soil texture	LS	SL

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Soil water characteristic curve

The suction plate method was used to set the matric potential at pF of 0, 1.0, 1.5, 1.8, 2.0 and 2.2, and the centrifuging method was used at pF of 3.0, 3.5, 3.8 and 4.2. Figure 1 shows the soil water characteristic curves of the deep layer soil and surface layer soil. Available moisture, i.e. the difference in volumetric water content at pF 1.8 and 3.5, was 10.3% for the deep layer soil and was 27.5% for the surface layer soil. Soil water holding capacity was incidentally improved by irrigation in the upland field.

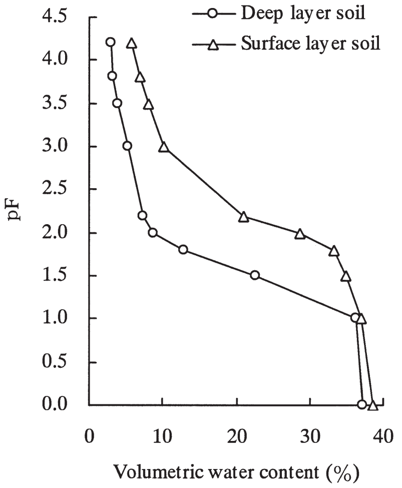

Fig. 1. Soil water characteristic curves.

Hydraulic diffusivity

Bruce–Klute method

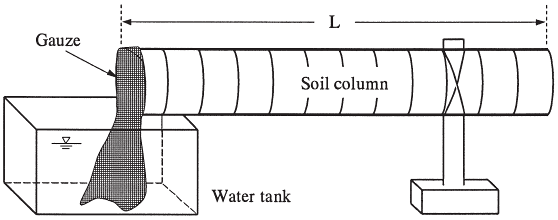

Fig. 2. Schematic view of experimental device for Bruce–Klute method.

Figure 2 shows the schematic view of an experimental device for the Bruce–Klute method. A column filled with a sample was placed horizontally. Water was supplied from a edge of column to the sample with a gauze immersed in a water vessel. After an appropriate lapse time, water supply was stopped, and the water contents of soil at different distances from the edge were measured. The relation between the distance and water content was used to obtain the soil water diffusivity related to soil moisture.

One–dimensional flow in the absence of gravity can be expressed with following equation.

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[D(\theta)\frac{\partial \theta}{\partial x}\right] \qquad (1)$$

Where θ is volumetric soil water content, $D(\theta)$ is soil water diffusivity, t is time, x is distance.

When hysterisis is not considered, soil water diffusivity can be expressed as Eq. (2) using the Boltzmann transformation.

$$D(\theta) = -\frac{1}{2}\left(\frac{d\lambda}{d\theta}\right)\int_{\theta_0}^{\theta}\lambda d\theta \qquad (2)$$

Where the function $\lambda(\lambda = xt^{-1/2})$ is constrained by an ordinary differential equation. The function $d\lambda/d\theta$ and $\int_{\theta_0}^{\theta}\lambda d\theta$ can be obtained from the relation between the distance from the edge and the water contents. Figure 3 shows the obtained results of soil water diffusivity.

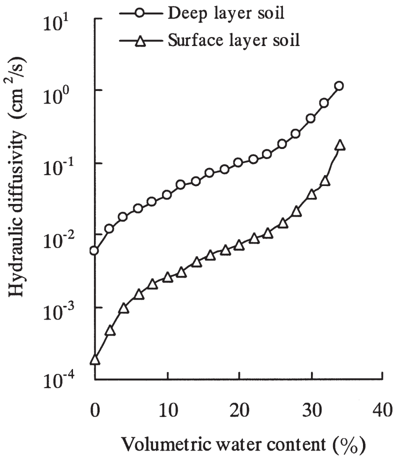

Fig. 3. Hydraulic diffusivity by Bruce–Klute method.

When the diffusivity at specific water content and the water content versus suction relationship for a soil are known, the unsaturated conductivity $K(\theta)$ is calculated by the following equation.

$$K(\theta) = D(\theta)\frac{\Delta\theta}{\Delta\Psi} \qquad (3)$$

Where $\Delta\theta/\Delta\Psi$ is the slope of the water content versus suction Ψ, relationship at the water content. The results were shown in Figure 4.

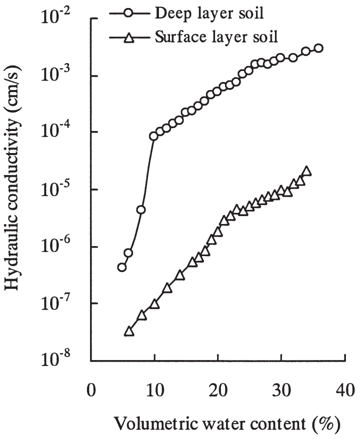

Fig. 4. Unsaturated hydraulic conductivity by Bruce–Klute method.

One–Step method

This method is based on measuring the falling rate of drainage from a sample on the tension–plate device. Figures 5 and 6 show the soil water diffusivity and hydraulic conductivity obtained by the One–Step method, rspectively.

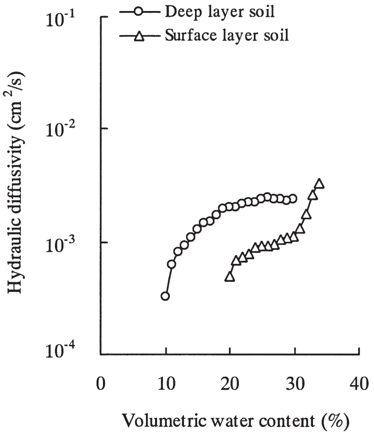

Fig. 5. Hydraulic diffusivity by One–step method.

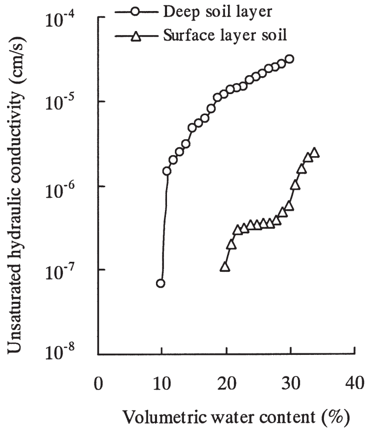

Fig. 6. Unsaturated hydraulic conductivity by One–step method.

Saturated hydraulic conductivity

The saturated hydraulic conductivity was measured with the constant head permeameter.

That of the deep layer soil was 1.67×10^{-3}cm/s which was the average of 13 times experiments in 5 minutes interval, and that of the surface layer soil was 2.69×10^{-5}cm/s which was the average of 14 times experiments.

Calculation of soil water flow

Soil water flow can be expressed as follow.

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[K(\theta)\frac{\partial(\Psi-z)}{\partial z}\right] \tag{4}$$

Introducing the diffusivity $D(\theta)$ into Eq. (4), we can rewrite as follow.

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[D(\theta)\frac{\partial\theta}{\partial z}\right]-\frac{\partial K}{\partial z} \tag{5}$$

Since $D(\theta)$ is defined as the ratio of the hydraulic conductivity to the specific water capacity, we obtain Eq. (6).

$$K(\theta)\frac{\partial\Psi}{\partial\theta}=D(\theta) \tag{6}$$

The soil water velocity v can be expressed by the Darcy' law as Eq. (7).

$$v=-K(\theta)\frac{\partial(\Psi-z)}{\partial z}=-D(\theta)\frac{\partial\theta}{\partial z}+K(\theta) \tag{7}$$

Thus, soil water flow Q in some depth that is the volume of water passing through a unit cross–sectional area during a time of dt can be expressed as Eq. (8).

$$Q=vdt=\left[-D(\theta)\frac{\partial\theta}{\partial z}+K(\theta)\right]dt \tag{8}$$

Simulation of vertical water infiltration

With a constructed simulation model, a vertical water infiltration was calculated using the experimentally measured data, water retention, hydraulic diffusivity and conductivity. Figure 7 shows the one–dimensional compartment model in which the soil layer of 30 cm depth was divided into 18 layers. Equation (8) was rewrite as following equation for programming.

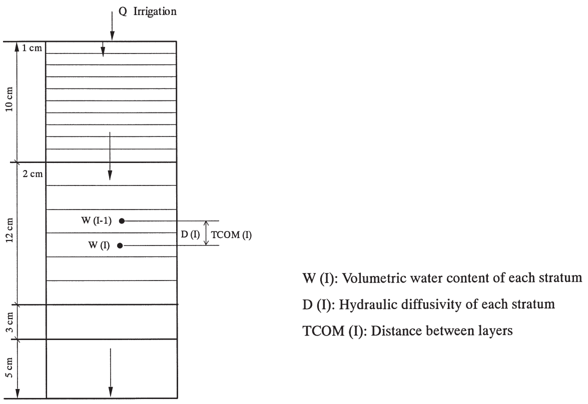

Fig. 7. Compartment model.

FLR(I)={−D(I)∗[W(I)−W(I−1)]/TCOM(I)
+K(I)}∗DELT (9)

Where FLR (I) is soil water flow between stratums, D (I) is diffusivity at each stratum, K (I) is conductivity at each stratum, TCOM (I) is distance between each layer, W (I) is volumetric water content at each layer and DELT is a time interval.

Water balance at a layer can be expressed as the following.

DFLR=FLR (I)−FLR (I−1) (10)

Figure 8 shows the change of profile of volumetric water content of the deep layer and surface layer soils during an irrigation period. The initial volumetric water

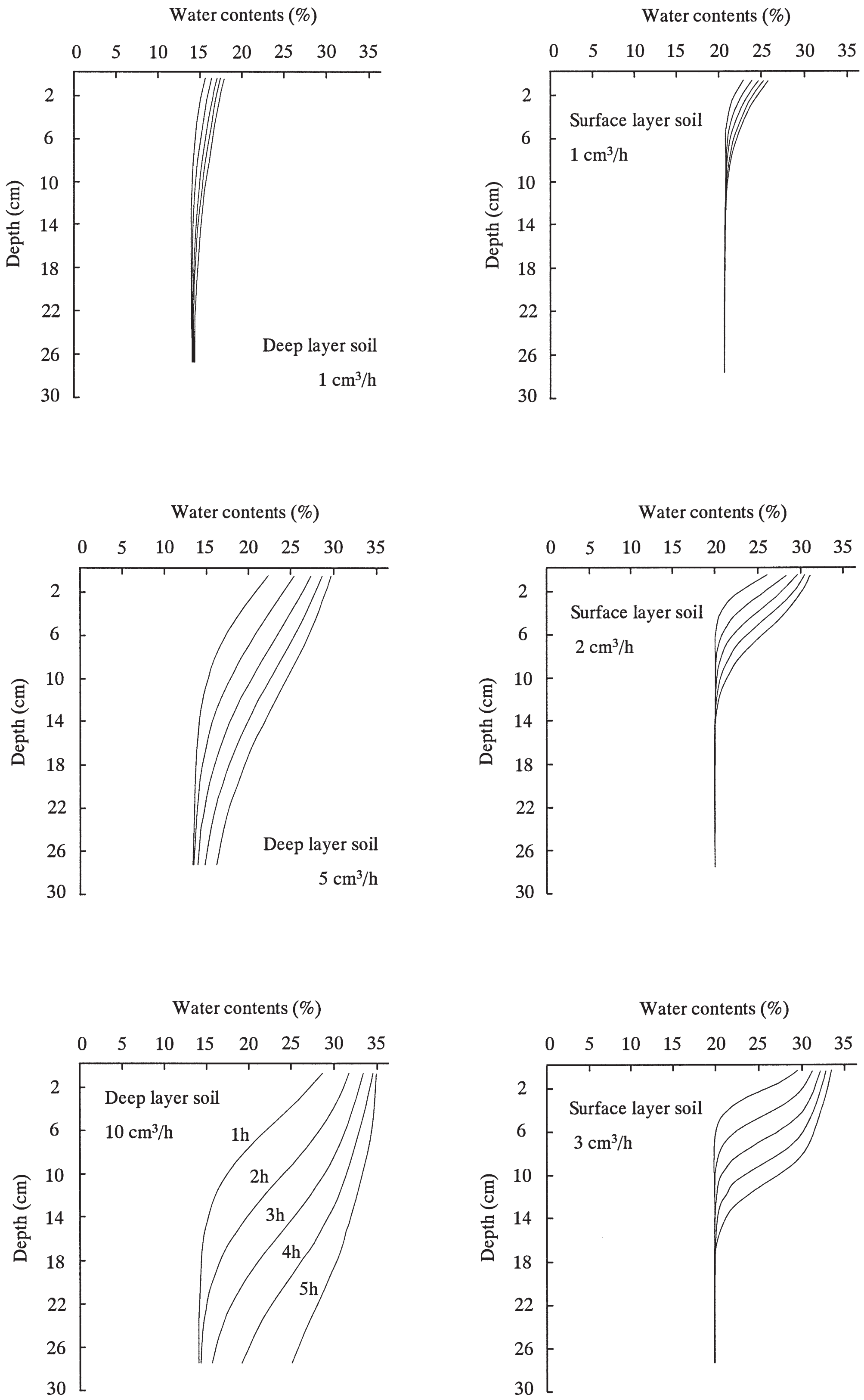

Fig. 8. Profile of volumetric water content for the deep layer and surface layer soils during irrigation.

content was 14% (pF1.8) and the irrigation rate was 1, 5 and 10 cm^3/h for the deep layer soil. The initial volumetric water content was 20% (pF2.2) and the irrigation rate was 1, 2 and 3 cm^3/h for the surface layer soil.

For the deep layer soil the soil water content increased rapidly at all depths because the hydraulic conductivity of was large. On the other hand, soil moisture moved slowly and wetting front could be seen clearly for the surface layer soil.

CONCLUSIONS

In this research, the water permeability of two soils, i.e. deep and surface layer soils, in an upland field of Tenggeli desert was measured, and a numerical study of infiltration process was conducted. The available moisture was 10.3% for the deep layer soil and 27.5% for the surface layer soil. Water retention of upland field soil was improved 2.7 times of sand. As a simulation results, the infiltration rate was slowly for the surface layer soil in comparison with the deep layer soil.

Crops and fruits can be grown continuously by proper irrigation even in the desert. These results obtained in this study will contribute to sustainable development of agriculture at the middle reaches of the Yellow River basin.

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