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Capillary Zone from a Watertable*

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Abstract

An artificial perched watertable was constructed by a watertable construction machine at about 0.5 m depth from the soil surface in an area where the annual precipitation occurs only in the summer season to retain summer runoff in this watertable. The zone of capillary diffusion from the underground watertable during dry season for seven months from September to March in which no rain occurs was determined in an indoor soil bin which had a transparent side and a float and needle system to maintain water at a constant level. The results showed that water proceeded quickly into a whole sand layer and then into a clay soil layer. When the capillarity diffused into three-dimensional clay soil layer, the maximum length of the capillarity was 4.1 m in horizontal direction and the minimum length was 0.95 m in vertical direction for the seven months. Hence, the distance required to operate the watertable construction machine was 11.2 m.

[Keywords] dry area, underground, water storage, capillarity, velocity of capillarity

I Introduction

The annual precipitation in the North of River, Inner Mongolia and Black Dragon provinces of People's Republic of China is only 400-700 mm. Moreover, the monthly rainfall is uneven; that is, about 60-70% of the annual precipitation occurs in July and August, and there is almost no rainfall in the winter and spring seasons. Plants often suffer due to excessive moisture during the growing season in the summer, and alternately, to drought during the seeding season in the spring. If heavy rain occurs in the summer season, the runoff flows on the soil surface and gathers at the lowest place in the field because soils in these areas are planosol (Araya *et al*., 1996), meadow soil (Zhang & Araya, 2001) and whitish oasis soil (Guo & Araya, 2002), which are quite impermeable. The lowest place becomes a pond during every rainfall, and the plants there are submerged at this time and all rain water cannot penetrate into the soil and becomes runoff loss on the soil surface, eventually flowing into the rivers. As a result, there is water in the rivers only in the rainy season of July and August in these areas.

By constructing an artificial perched watertable at about an 0.5 m depth from the soil surface as described in the previous papers (Araya & Guo, 2002a; 2002b), it was intended to hold the runoff caused in the summer preferentially in this watertable, thus preventing excess moisture loss. The water in the artificially permeable layer could be available for crops and grasses as capillary water in the dry spring season.

To accomplish this, a machine to construct the artificial perched watertable (watertable construction machine) was designed and built (Guo *et al*., 2004a). This paper deals with the zone diffused by capillary water from the watertable during the dry season which was determined in an indoor soil bin where the water diffusion line could be easily observed through the glass side. From this capillary zone, we can determine the distance required to operate the watertable construction machine in an actual field.

II Theoretical Consideration of Capillary Diffusion

1. Resistance pressure determined by soil cell

Soil was placed in the soil cell (Jia *et al*., 2006), and by

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applying a flow of air, the resistance gauge pressure caused by soil p_{af} was determined. With this value of p_{af}, the mean diameter of the soil and the capillary speed can be calculated as described below. The relationship between the air mass flow rate G_a in kgs^{-1} and the resultant pressure p_{af} in Pa is obtained as (Jia *et al*., 2006)

$$p_{af} = \frac{k_1 b \mu_a G_a}{A_c \rho_a (\varphi d_m)^2} \cdot \frac{1}{\varepsilon(1-s)} \quad (1)$$

where b is the thickness of the soil cell in m, μ_a is the coefficient of viscosity of air in Nsm^{-2}, A_c is the sectional area of the soil cell in m^2, ρ_a is the air density in kgm^{-3}, φ is the shape factor of soil particles, d_m is the mean diameter of soil particles in m, ε is the soil porosity, s is the degree of saturation and k_1 is the hydraulic constant of the soil cell (apparatus).

Glass beads of 1 mm or 2.5 mm diameter d_m with smooth surface (φ=1) were charged in the soil cell, and the values of p_{af} were determined. Value of k_1 was calculated from Eqn (1), and the mean value was 600 (Jia *et al*., 2006).

The compressibility of air should also be considered in Eqn (1). It is assumed that the average values of the air density at the inlet ρ_{af} in kgm^{-3} and that at the outlet ρ_{a0} in kgm^{-3} are correct. The air density ρ_a is obtained from the characteristic equation for a perfect gas

$$\rho_a = \frac{\rho_{af} + \rho_{a0}}{2} = \frac{p_{af} + 2p_{a0}}{2R(273+t)} \quad (2)$$

where p_{a0} is the absolute atmospheric pressure in Pa, R is the gas constant of air in Jkg^{-1}K^{-1} and t is air temperature in °C.

The specific surface area S_v in m^{-1} is defined (Shirai, 1973) as

$$S_v = \frac{\pi(\varphi d_m)^2(1-\varepsilon_a)}{\frac{\pi(\varphi d_m)^3}{k_2}} = \frac{k_2(1-\varepsilon+\varepsilon s)}{\varphi d_m} \quad (3)$$

The denominator of Eqn (3) is the unit bulk soil volume, and the numerator is its total contacted surface area. ε_a is air porosity [$=\varepsilon(1-s)$]. k_2 is a constant for Eqn (3) from which S_v is calculated.

With Eqns (1) and (3),

$$S_v = \sqrt{\frac{k_2^2(1-\varepsilon+\varepsilon s)^2 \varepsilon(1-s) A_c \rho_a p_{af}}{k_1 b \mu_a G_a}} \quad (4)$$

or

$$k_2 = \frac{S_v}{(1-\varepsilon+\varepsilon s)} \sqrt{\frac{k_1 b \mu_a G_a}{A_c \rho_a p_{af}} \cdot \frac{1}{\varepsilon(1-s)}} \quad (5)$$

The glass beads of 1 mm (S_v=10^{-3} m^{-1}) or 2.5 mm (S_v=400^{-1} m^{-1}), whose S_v values were known, were charged in the soil cell as mentioned above, then the values of p_{af} were measured, and the values of k_2 were calculated. The mean value of k_2 is 2.0, and so two constants (k_1=600 and k_2=2) are used when the physical properties of the soils are determined.

2. Diameter due to specific surface area of soil particles and hydraulic radius of porosity

The diameter due to specific surface area d_v in m is defined as the reciprocal number of S_v [Eqn (4)]

$$d_v = \frac{1}{S_v} \quad (6)$$

The hydraulic radius of its porosity r_p in m of the soil particles with the diameter due to specific surface area d_v is obtained as

$$2r_p = \varepsilon_a d_v = \varepsilon(1-s)d_v \quad (7)$$

3. Capillarity

Based on previous studies (Washburn, 1921; Ridal, 1921; Richards, 1931; Hamraoui & Nylander, 2002; Lu & Likos, 2004), the capillarity diffused in the three-dimensional directions in Fig. 1 was analysed here.

The volume of the water dQ in m^3 which flows through any cross-section of the capillarity over time dτ is obtained as (Fujimoto, 1962)

$$\mathrm{d}Q = \frac{\pi k_p^4 r_p^4 \sum P}{8\mu_w l} \mathrm{d}\tau \quad (8)$$

where ΣP is the total effective pressure in Pa, μ_w is the coefficient of viscosity of water in Nsm^{-2}, l is the real length of water column in capillarity in m, and k_p is a correction coefficient of the hydraulic radius which corrects r_p to agree with the measured capillary length.

In Eqn (8), inertia force is neglected because the moving velocity of water in the soil by capillarity is very slow (Washburn, 1921).

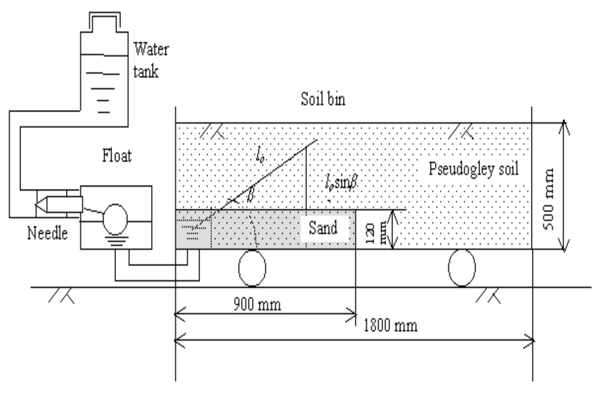

Fig. 1 Capillarity of coastal sand and pseudogley soil (heavy clay) in a three-dimensional soil bin. l_0, observable capillary length; β, angles drawn on glass side.