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Analysis of Fibrous Interface Capillary Irrigation System Using HYDRUS 2D/3D for High Water Saving Agriculture

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ABSTRACT

Capillary irrigation has been considered as one of the best irrigation techniques in water saving agriculture. It is due to its high efficiency in water supplying method which provides many benefits, especially in areas that have a limited water supply. In capillary irrigation, a fibrous interfaced capillary is a relatively new method that needs a detailed understanding of infiltration process. An optimized design of fibrous capillary system needs the judicious combination of fibrous design, discharge rate, irrigation duration and the time interval between the consecutive irrigations. To this aim, a numerical modeling method using HYDRUS 2D/3D software will represent a powerful tool to analyze the evolution of the wetting and exploration of capillary irrigation management strategies, to optimize the water usage. The model is tested and verified at the scale of a single pot using various fibrous design and root uptake level. The result shows that the application of fibrous capillary system is able to provide a sufficient water supply at various plant growth stages.

KEYWORDS

Capillary irrigation, Infiltration, Soil wetting pattern, HYDRUS 2D/3D

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INTRODUCTION

Crop irrigation is becoming a main interest in agricultural research due to the water shortage crisis and climate change to support the global food demand. A limited source of water had become a major constraint to enhance the food production in order to fulfill the global food demand in addition of the steadily increment of world population every year. Agriculture activities consume about nearly 70 % of fresh water for crop irrigation (FAO, 2009a, 2009b). With a limited water source in agricultural field, farmers are not able to double their production unless an important strategy is executed to enhance the current irrigation system. Therefore, researchers need to find a new method to supply water based on the plant water demand by adopting a precision irrigation system.

The precision irrigation system is an analytical tool to help the farmers to reduce the water usage and enhance crop management irrigation system (Balafoutis et al., 2017). This technique uses a drip irrigation system as it is able to supply water directly into the root zone. Advance fabric technology recently allows this new method of delivering water by using a fibrous based capillary flow which can also be categorized as a subsurface irrigation. The fibrous system delivers water by capillary movement from a reservoir to the growth medium. This method can minimize the cost of labor, time and water compared to the conventional watering system.

The fibrous irrigation system supply water based on the amount of plant water demand, which is suitable for regulating plant water stress. There are many researches related to capillary irrigation design to minimize the water supply at the root zone (Kinoshita & Masuda, 2011; Lee et. al, 2010; Schuch et. al, 2008; Semananda et. al, 2016; Abidin et al., 2014). The efficiency of nutrient absorption and water usage is generally higher by using subsurface irrigation as water leaching will be reduced. Water leaching degrades the irrigation system as it reduces the amount of nutrients that will be supplied to the plants. It is important in irrigation system to minimize the nutrient losses through leaching by the synchrony and synlocation of nutrient uptake by the plant with nutrient supply from soil and fertilizer (Lehmann & Schroth, 2003). With infiltration control and soil wetting level, leaching in capillary irrigation can be avoided and the plant can maximize the absorption of nutrients to provide a good quality of fresh produce.

A proper fibrous interface design requires knowledge of water distribution pattern around the medium that match the root zone. The exact shape of the wetted volume and water distribution depends on many factors, including soil hydraulic conductivity, initial soil conditions, discharge rate, application frequency, root characteristic, evaporation and transpiration (El-Nesr et. al, 2014; Subbaiah, 2013). However, the wetting pattern depends on the location of the water source with respect to the soil surface. In designing a capillary irrigation system for the crop, the dimension of the wetted volume and the distribution of soil moisture within this volume are the two main factors in determining a suitable water supply depth to obtain an optimum distribution of water in the root zone.

This paper presents the model of fibrous interface and simulation to analyze the water distribution and soil wetting under the fibrous capillary. The model is used to investigate the relationship between the water supply depth and soil water content that are affected by the fibrous interface irrigation design and management. The simulation and analysis of the design has been conducted using HYDRUS 2D/3D software package.

MATERIALS AND METHODS

Fibrous wicking model integrated water interface model

Figure 1 shows the concept of the fibrous capillary system integrated with type X water interface. The capillary flow is used to supply water into the root zone. In soils, water moves upward through a soil pore space between the soil particles. In simulation, the water supply depth (Δh) is placed at three different levels and the amount of water inside the water interface tank is kept constant. Figure 1(b) and 1(c) show the prototype of capillary irrigation and the water interface type X. The water interface X has a surface area of 80 cm^2 and the fibrous strip has a size of 3 cm x 0.1 cm x 12 cm. The lower part of the fibrous sheet is immersed in water at a different water supply depth (Δh) to investigate the water distribution.

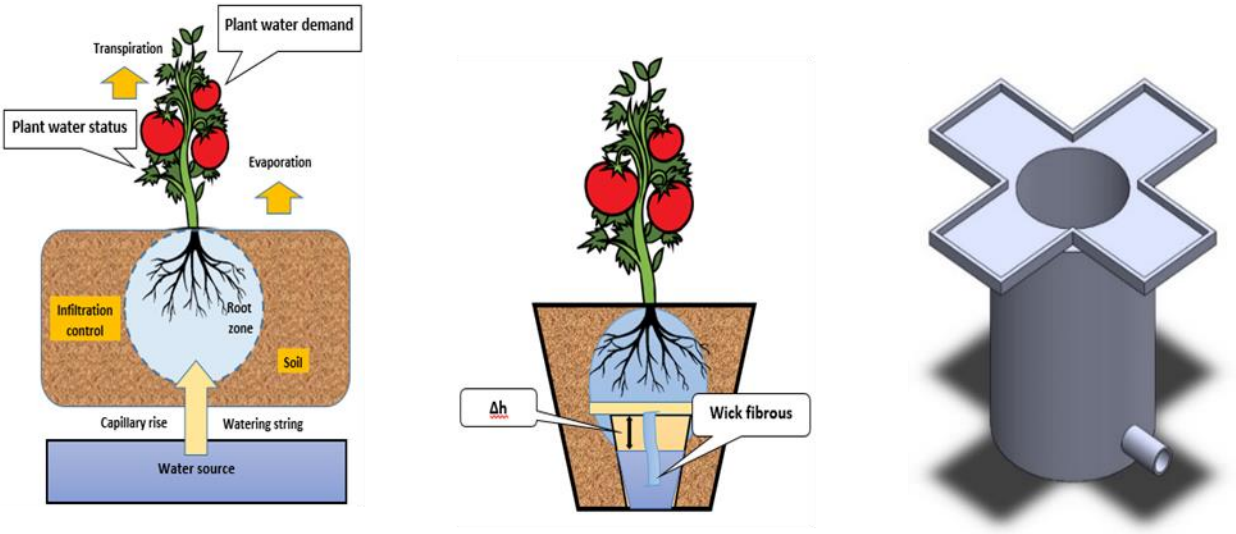

Figure 1: (a) Fibrous irrigation model, (b) Prototype capillary irrigation, (c) X water interface design

Soil Water Flow Model and Simulation

The HYDRUS (2D/3D) software package (Šimůnek et. al, 2016) simulates variably saturated and unsaturated water flow in porous media by solving the mixed from Richard Eq. (1) using a Galerkin finite-element method (Celia,et. Al 1990)

$$C(h)\frac{dh}{dt} = \frac{d}{dx}\left[K(h)\frac{dh}{dt}\right] + \frac{d}{dy}\left[K(h)\frac{dh}{dy}\right] + \frac{d}{dz}\left[K(h)\frac{dh}{dz}\right] + \frac{dK(h)}{dz} \quad (1)$$

Where θ = volumetric water content (L3L-3); h = soil water pressure head (L); t = time (T); x = x horizontal space coordinate (L); y = y horizontal space coordinate (L) and z = z vertical space coordinate (L) and K = hydraulic conductivity (LT-1). HYDRUS was used to simulate the water infiltration and redistribution from the fibrous sheet source. The soil and the fibrous sheet hydraulic properties in HYDRUS are based on the van Genuchten (1980) model:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{(1+|\alpha h|^n)^m}, & h \geq 0 \\ \theta_s, & h \geq 0 \end{cases} \quad (2)$$

$$K(h) = K_s S_e^l [1 - (1 - S_e^{\frac{l}{m}})^m]^2 \quad (3)$$

Where θ_r and θ_s are the residual and saturated water content(L3L-3), respectively; K_s is the saturated hydraulic conductivity(LT-1); α is an empirical constant that is inversely related to the air-entry pressure value (L-1); n is an empirical parameter related to pore-size distribution (unit less); l is an empirical shape parameter; m=l-1/n (unit less); and Se is the effective saturation given by:

$$Se = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (4)$$

The whole domain was simulated with the fibrous sheet system located on the middle bottom of the soil. The transport domain for which the numerical simulation was obtained is a cylinder (22 cm diameter and 18 cm height) which was discretized into the automatic node using smaller spacing within the soil and the fibrous sheet system (Figure 2). The finite element mesh was generated using the automatic triangulation algorithm that is implemented in HYDRUS. Hydraulic parameters ($\theta_r, \theta_s, \alpha, n, l$) for nodes representing the soil were determined by using the RETC function that is provided in HYDRUS based on the data of θ-ψ relationship.

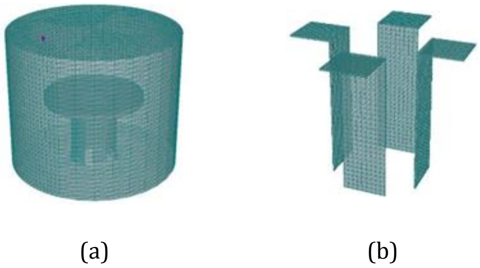
(a) (b)

Figure 2: Mesh Analysis (a) Loam soil medium, (b) Fibrous strip X shape

The hydraulic conductivity of each fibrous sheet was measured by using Larose method while the θ-ψ relationship was determined using column test method. The hydraulic parameters (θ_r, θ_s, α, n, l) for nodes representing the fibrous were determined using RETC based on the θ-ψ and the result are in Table 2.

Table 1. Hydraulic parameters for the material used in the simulation

Type	θ_r (cm^3/cm^3)	θ_s (cm^3/cm^3)	α (cm^{-1})	n	l	Ks (cm/h)
Loam	0.078	0.43	0.036	1.56	0.5	24.56
Fibrous Sheet	0.001	0.9794	0.14761	2.86012	0.5	56.44

The bottom boundary of the vertical strip was assigned a constant pressure head equal to the pressure head imposed in the experiment when the water supply depth was set -3, -5 and -7 cm respectively. The model part was set to the zero-flux boundary and the water content measurements were set to pressure head values at -100 cm using the soil water retention characteristic given by Eq. 2. The initial profile of the fibrous system and soil was assumed uniform in the vertical and horizontal direction. The fibrous sheets were assumed to be initially saturated.

RESULTS AND DISCUSSIONS

Soil water distribution and distribution processes

Figure 3 shows the simulated soil water content distribution in a vertical plane with fibrous capillary sheet water interface at various water supply depths. The infiltration process was shown only in the half area between the fibrous capillary strips. The location of fibrous capillary sheet at the centre of the medium act as a water source where the soil moisture content gradient was observed. The wetting area moved out from the fibrous sheet during the infiltration process. In general, the wetting front increase as the water supply depth decreased where wetted width and depth were affected by the discharge rate of water source. It is due to the increasing discharge rate as the volume of water that was supplied in each duration increased that creates a higher volume of wetted zone.

The pattern of water distribution for each water supply depth in every hour has a different wetted zone area. For water supply depth of -3 cm and -5 cm, the wetting front reach the soil surface after 4 and 10 hours of irrigation time while the water supply depth of -7 cm unable to reach the soil surface due to the slower discharge rate. The slower discharge rate helps to reduce the water loss due to evaporation and prohibits the growth of weed on the soil surface at the same time. It is also important to determine the suitable amount of water supply depth in wetted zone area by defining the amount of root water uptake based on different plant growth stages to increase the efficiency of irrigation system. The water saving criteria in fibrous capillary integrated water interface system could be achieved by manipulating the amount of water supply depth. For numerical analysis in this study, the different level of water supply depth is able to estimate the irrigation condition based on various amount of plant water demand.

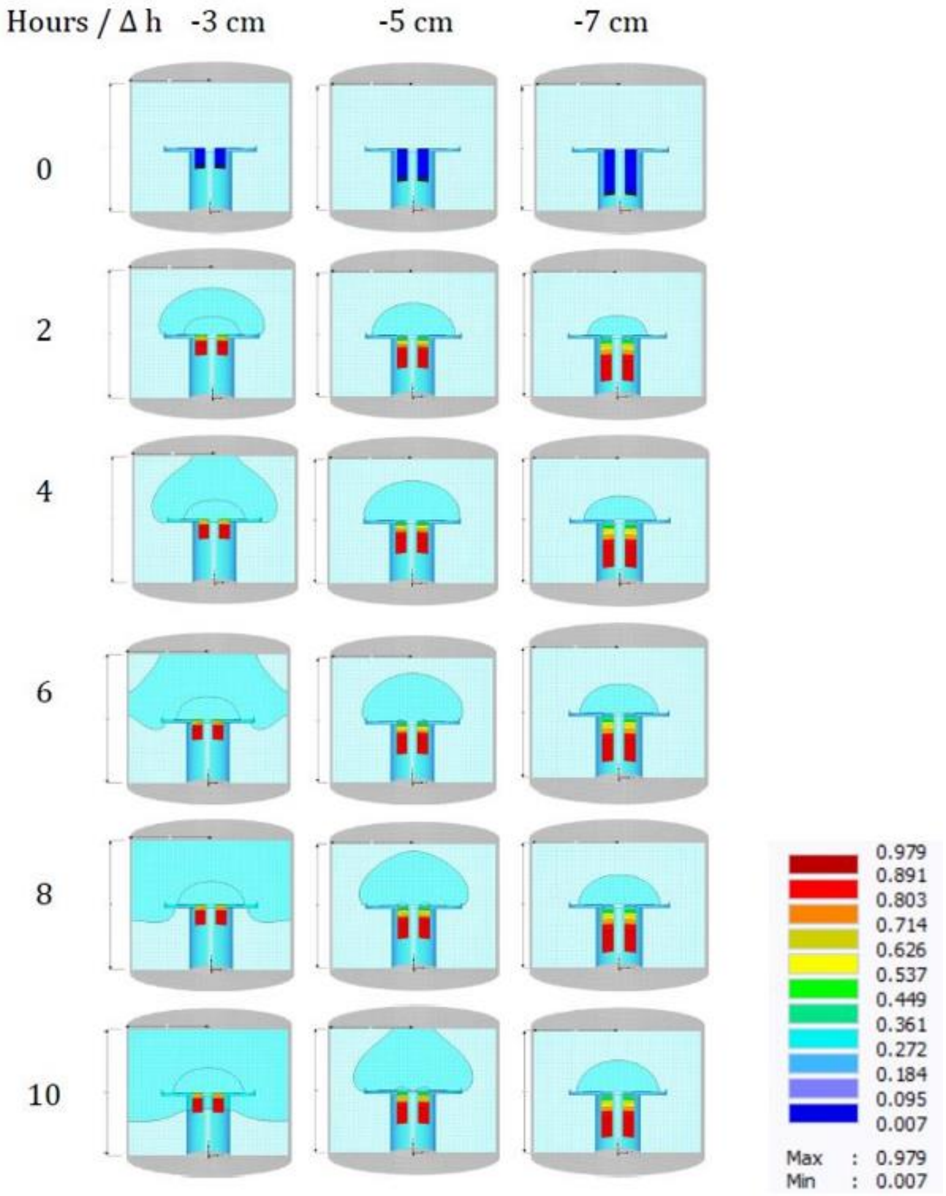

Figure 3: Comparison of the simulated distribution of volumetric soil water content (cm/cm) for fibrous capillary irrigation integrated water interface X.

Cumulative infiltration

Figure 4 shows the simulated cumulative infiltration of water volume entering the loam soil from the fibrous capillary system with a constant Δh at -3, -5 and -7 cm. The cumulative infiltration decreases exponentially with time until it reaches steady state. These indicate the effectiveness of fibrous strip supply water as loam soil has a different infiltration rate with changing water supply depth. Therefore, based on this result, the water saving system based on root water uptake can be applied to this system by manipulating the water supply depth. The infiltration capacity for water supply depth of -3cm is found to have a highest infiltration volume at 342 ml. It is due to the lower distance measured between the water supply depth level and soil contact surface. Therefore, if the water source is located near to the area of soil bottom surface, the infiltration will execute faster, thus allows higher amount of water to flow through the fibrous strip

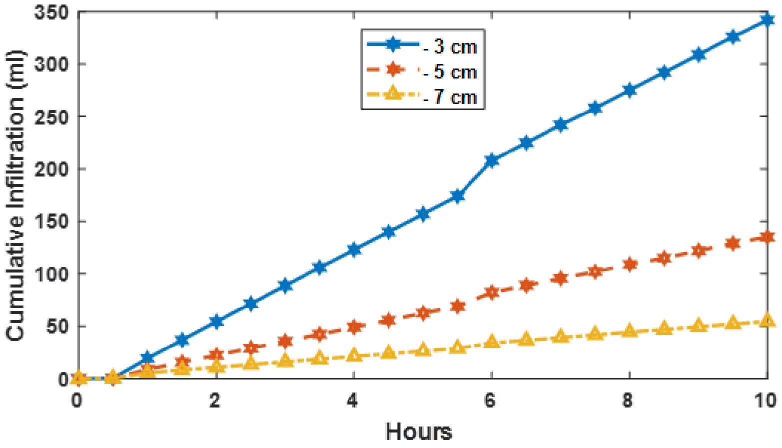

Figure 4: Predicted cumulative infiltration after 10 hours of infiltration with a constant Δh at -3, -5 and -7 cm.

Soil moisture profiles

The comparison between various water supply depths and soil moisture contents for 10 hours operation of fibrous capillary water interface is illustrated in Figure 5. The result shows that soil moisture content shows a different time taken to achieve the steady state condition. The maximum amount of soil water content for water supply depth at -3cm, -5cm and -7cm are 0.399 cm^3/cm^3, 0.360 cm^3/cm^3 and 0.319 cm^3/cm^3 respectively. The increment amount of water content is due to the redistribution process where large differences in matric potential drive water into the soil profile. However, after an hour of irrigation, the soil water content reaches the steady state at a different value. This reflects the potential of water infiltration at the soil where every level of water supply depth has the maximum discharge rate and increases the ability to store water and the capillary will rise where the water moves upwards through the fibrous strip. The water holding capacity is depending on the capillary action and the size of the pores between the soil particles.

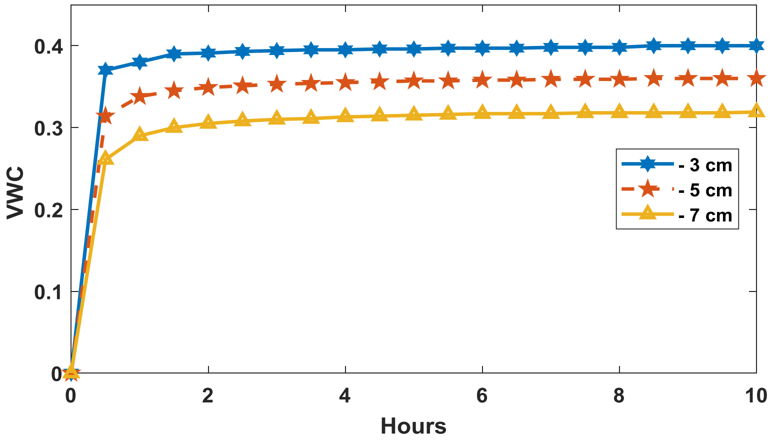

Figure 5: Predicted soil moisture content after 10 hours' irrigation of infiltration with a constant Δh at -3, -5 and -7 cm

Discharge rate fibrous capillary irrigation integrated water interface X

Figure 6 shows the predicted discharge rate of fibrous capillary irrigation system integrated water interface X after 5 hours irrigation duration with a constant Δh at -3, -5 and -7 cm. The first-hour irrigation shows that the rate of discharge for 3 types of water supply depth increase drastically with different rates of water flow in the medium. The result shows that the highest discharge rate is at -3 cm level, which has the irrigation volume of 18.74 ml. For the water supply depth at -5 cm and – 7cm, the highest peak discharge rate volume is 8.362 ml and 5.208 ml respectively. The discharge rate speed reflects the distance between the water source and soil bottom surface at fibrous strip water interface X. When the water flows into the soil, the infiltration process is becoming slower as the infiltration rate decreases over the time as the soil becomes saturated. In addition, hydraulic conductivity decreases as the water content and soil water pressure head decreases. However, the discharge rate is found to be decreasing after 1 hour and has a steady state condition after a long period of irrigation. The simulated discharge rate for the water supply depth are 17 ml per hour for -3 cm, 6.7 ml per hour for -5 cm and 2.5 ml per hour for -7 cm respectively. The intake rate decreases with steady infiltration rate because the soil is gradually become saturated.

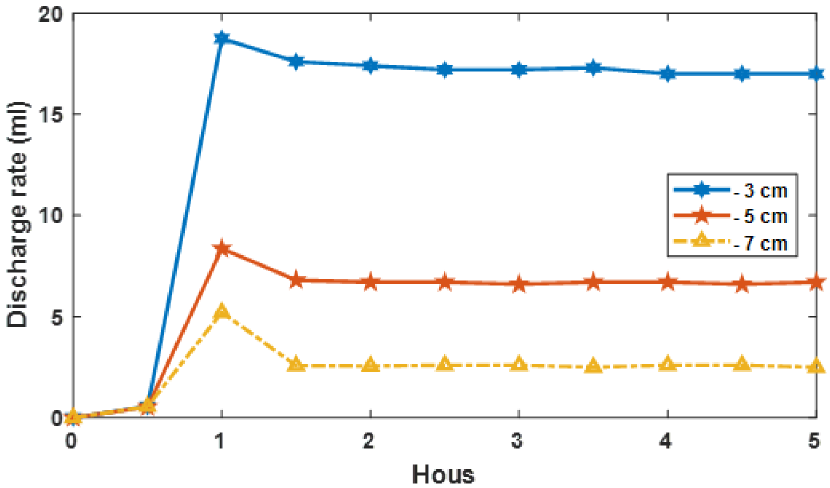

Figure 6: Predicted discharge rate fibrous capillary irrigation system integrated water interface X after 5 hours duration irrigation with a constant Δh at -3, -5 and -7 cm.

CONCLUSIONS

Numerical simulations are conducted in this study that indicates the importance of the fibrous interface system design in water distribution and soil wetting zone. The water distribution using a fibrous capillary irrigation system integrated with water interface X is affected by the soil physical, hydraulic properties and water supply depth system management. Different water supply depths in the soil produce different reaching area of the wetting front, soil moisture content and discharge rate. The surrounding soil moisture and discharge rate infiltration computed different results for the optimal irrigation system based on plant water demand. The placement of the water supply depth is important to provide an effective soil wetness in the root zone based on growth. The simulated result shown that the water supply depth is differentiated into several categories based on plant growth and plant water demand to provide a higher efficiency of water saving irrigation system. Further analyses via HYDRUS were conducted to study the relationship of various design parameters and soil texture in designing an optimized fibrous interface system.

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