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Study on the characteristics of moist soil under the condition of water supply of surface capillary

In order to explore the characteristics of moist soil under the condition of water supply of surface capillary, this research constructed device which screen the capillary source infiltration based on the tests. Embedding TDR monitoring instrument in the indoor soil box, it can detect the characteristics of moist soil under the conditions of different capillary source infiltration water percolating capacities. The results show that there is a power function relationship between the cumulative infiltration quantity and time under the condition of water supply of surface capillary. The wetting front pushes forward like semi ellipse curve, and the moist soil presents like approximate semi ellipsoid. When the infiltration time and infiltration rate are constant, the soil water content in the infiltration point tends to a stable value, the soil water and heat coupling movement is complex, and the numerical variation tendency of each monitoring point is similar. Based on the above results, we construct empirical solution equation to predict the eigenvalues of soil wetting body under the condition of water supply of surface capillary. In this research, the capillary source infiltration material is found, and the surface capillary source water supply device with low cost and high efficiency is constructed. The device makes the growth of plants with enough water for the first year, but it can still keep the roots dry enough to make the seedling root down. Preventing soil evaporation loss, slowing down water loss of the surface micro environment of the mainland and other bad influence, the device can improve the efficiency of water use. Meanwhile, the device can effectively enhance the ability of seedlings against high temperature of the surface in desertification area, wind-blown sand, animal browsing stress, damage, and create a proper environment for the normal growth of plants, which enjoys broad prospects.

Keywords: Water supply of surface capillary; wetting body; wetting front; soil water content; empirical solution.

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1.0 Introduction

Dealing with the ecological problems caused by food shortage, soil erosion and global climate change is the focus of attention at throughout the world. Soil moisture is the key factor which influences whether the normal growth of plants. Study on soil water infiltration not only contributes to the development of the unsaturated soil water infiltration and transfer theory research, but also to the comprehensive evaluation of the surface water and groundwater resources. So it can provide scientific basis for reasonably determining irrigation technical parameters. Soil water infiltration is a process where water passes through all or part of the surface, and it flows below the surface into soil, then it moves and stores in soil, finally it changes into soil water. This process is an important part of reciprocal transformation among the atmospheric precipitation surface water, soil water and groundwater. And it is affected by surface conditions, soil properties, etc. Cote [1] and his partners apply Hydrau 2D software to analyze the condition of soil water and solute migration under drip irrigation; Pztel Neelam [2] and his partners builds a dynamic soil water movement model of subsurface drip irrigation; Zhang Zhitao [3] and his partners propose that bulk density brings greatly productive significance to the design of bubble root irrigation system and the choice of the spacing and width of field layout. Guan Yao [4] and her partners utilize automatic measurement system to detect soil point water infiltration wetting process; Zhang Lin [5] and his partners study the regulation of soil water movement with drip irrigation of multiple point sources; Zhu Delan, Yue Haiying [6] and their partners study the characteristics of soil water distribution and the distribution regularity of water content in soil wetting body, propose a mathematical model that horizontal and vertical diffusion of different soil moisture changes with time, and point out that there is a power function between soil wetting volume and irrigation. Guo Weidong [7] and his partners study the regularity of soil water movement under the condition of node infiltration irrigation; Zhang Jianfeng [8] and his partners study that different opening ways cause infiltration characteristics of soil with deep pit infiltration irrigation, and they think that opening ways bring great effect on the distribution of soil water content; Zhao Weixia [9] and her partners raise a mathematical model of wetting body under non-pressure irrigation, and utilize the capillary principle of soil to supply plants with water. Although applying drip irrigation and infiltrating irrigation to save water is obviously efficient, it costs too much at the early stage. Non pressure irrigation, moist tube irrigation and drip irrigation can save energy, but they cannot be put into practical use in mountain areas and hilly grounds because it is too complex to lay the pipelines.

Therefore, based on the principles of capillarity and the tests which screen the capillary source infiltration, researching and developing surface capillary source water supply device, embedding TDR monitoring instrument in the indoor soil box to detect the dynamic changes of soil moisture content, soil wetting body, soil temperature under the conditions of different surface capillary source infiltration. They research and analyze these phenomena so as to provide scientific basis for the development of capillary infiltration device to save more water, to solve the problems that plants grow unhealthy in harsh environment at the early stage, and offer more effective solutions to improve the ecological environment.

2. Materials and methods

2.1 The place and time of experiment

The place of experiment: The laboratory in College of Water Conservancy and Hydropower Engineering, Sichuan Agricultural University. The time of experiment: From March 2016 to October 2016.

2.2 Research and development of water supply device

Using the cylindrical barrel made from polycarbonate (PC) as a water container, whose diameter is 30-50cm and maximum volume is 20L (Fig.1). The barrel wall is vertically marked with degree scales, and it is easy to observe and record the infiltration of water. There is a hole of 5mm diameter at the bottom of the barrel, which is jam-packed with strips of cloth (length of 11cm, width of 2cm). And the strips of cloth connect water with soil, so that water in the barrel can be continuously supplied for soil under the capillary action.

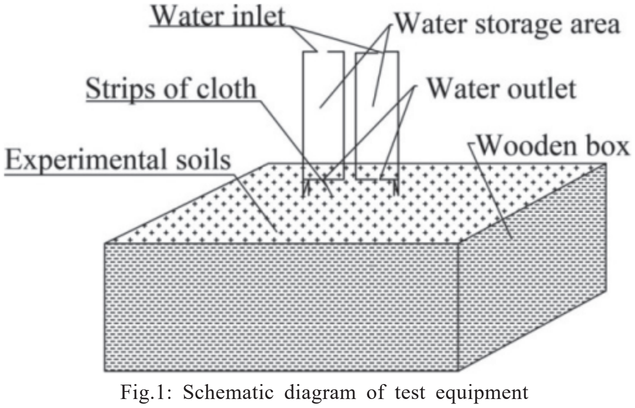

Fig.1: Schematic diagram of test equipment

Table 1: Selection of water supply materials

Fabric type	Pore size (mm)	Amount of infiltrating water (mL)	Infiltration rate (mm/d)
Polyester fiber	5	550	0.32
Crepe	5	550	0.15
Bamboo charcoal Cotton cloth	5	550	0.35
Baft	5	550	0.30
Composite cloth	5	550	1.31
Towel cloth	5	500	0.52

2.3 Screening of the materials of capillary source infiltration

Screening of cloth's material connecting bucket and the soil is very crucial to the above device. Using the control variable method, the capillary infiltration effect of different fabrics is determined by free infiltration test (Table 1). The results show that the infiltration rate of domestic composite cloth is the best when the hole is opened to 5mm. The domestic composite cloth is selected as capillary source infiltration material.

2.4 Experimental soil

We select powder sand of Yucheng region in Ya'an to test and research, we find that the content of the sand, clay and silt is 27.07%, 17.24%, 55.69%; the content of organic matter is 23.66g/kg; the density is 1.20g/cm^3; the total porosity is 54.72%. After drying the sand naturally, screening through 1.5cm×1.5cm aperture, removing obvious disturbances such like large stones and debris. Then we put the natural drying soil into the experimental wooden case which is 2m long, 1.4m wide and 0.6m deep (a total of 1.04m^3). To ensure the soil is as deep as plough horizon, the soil is 0.6m thick, and its radius of surface layer is a circle of 30cm. Under the good ventilation conditions, the content of initial soil moisture is measured as 3.1%.

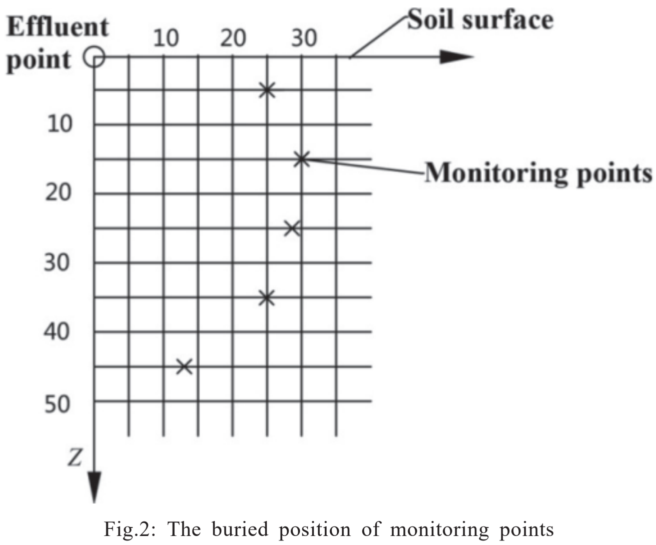

Fig.2: The buried position of monitoring points

2.5 The design of test and monitoring of soil water content

Before the experiment, we build three-dimensional coordinates and determine a three-dimensional coordinate system on the Circular Mound. Taking out a longitudinal section of the Circular Mound (Fig.2), embedding the i1#-5#TDR monitor into the soil in turn according to (25, 5), (30, 15), (27, 25), (25, 35), (13, 45) coordinates. TDR monitor automatically stores data, and the length of data record is set to 5 minutes.

The water supply device is arranged on the central mound, the water outlet is located in the origin of the coordinate system. The test is divided into two groups, and we add water into the device for 4 times, the content of water is respectively 17L, 8L, 8L and 3L. In the process of each irrigation and free infiltration, we record the changes of water infiltration. After each irrigation, we observe the changes of instrument readings. When the values of 5 monitoring points obviously decrease, we derive the data and analyze the moisture content and temperature changes at the monitoring points. After the test, we excavate all wetted soil along the central axis, measure the corresponding test index, and use the implementation of 3D coordinate measure the pushing distance of wetting front (coordinates). When the above test is completed, we carry out the same infiltration test respectively in the 4 corners of the box, and detect the corresponding index. Repeat each group for 3 times, and take out average value as test result to analyze.

3.0 Results and discussion

3.1 The characteristics of infiltration rate variation

The process of capillary water infiltration experience two stages – rapid rise and slow increase (Fig.3).

We can obtain from Fig.3, (1) the 8L-infiltration-rate infiltration curve is more stable than the 17L-infiltration-rate infiltration curve after a rapid rise stage. It indicates that the cloth is dry, the pores open, the water potential of soil has large gradient, the infiltration is rapid [10]; as the infiltration time extends, the pores of cloth are filled with water. Soil moisture increases, infiltration rate decrease. (2) The change of environment temperature has notable influence on the

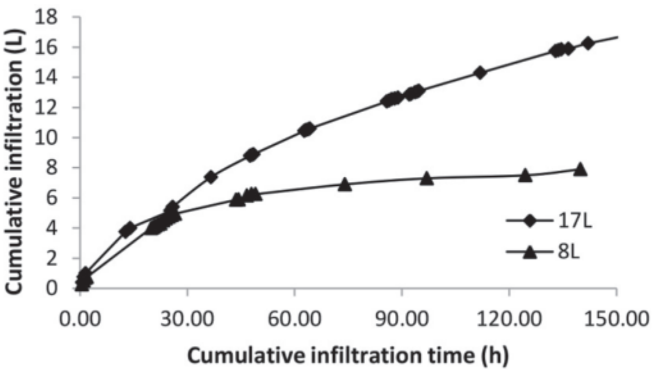

Fig.3: The relation between infiltration and time

infiltration rate: the cumulative amount of infiltration is 17L, ambient temperature is higher (22-35ºC), the pores of cloth expand, and the infiltration rate is high; the cumulative amount of infiltration is 8L, ambient temperature is lower (20-25ºC), the viscosity of water increases. Capillary migration rate of water in the pores is slow and the infiltration rate is low, so the latter curve tends to be slowed down. (3) The power function of correlation coefficient between cumulative infiltration and time is the highest. When infiltration time is long enough, the infiltration rate tends to be zero, which marks the end of infiltration. This result coincides with the results of Liu Chuncheng [11] and other scholars (4). Compared to the conventional way of water supply, the water supply device supply water by using both the changes of soil water potential and capillary effect of cloth [12]. After the cloth is soaked into water rustic contact surface, have certain effect on the perception of air temperature and humidity, the cloth used as a water supply channel, according to changes in the external environment of water process demand, by changing the number of pore size to control water, to maintain normal plant germination of water required has practical significance.

3.2 Spatial and temporal dynamic characteristics of soil water content

The curve of moisture content measured by 1#–5#TDR monitor is shown in Fig.4. (1) In the process of infiltration, the change of soil water content in a buried depth generally experiences 4 stages–stability, sharp rise, slow increase and stability. (2) The rise point in the phase that rate of soil water content sharply increases is closely related to the distance from the point of TDR buried monitor to the capillary source infiltration point. The farther the distance is, the longer the time of phase that moisture content increase sharply is, and vice versa. The main causes: At the initial stage of capillary water infiltration, the capillary voids of cloth are big. The water potential gradient of dry soil is low, capillary water mainly migrates laterally. With the extension of time, capillary water completely fills the pores of soil. After reaching the conditions of infiltration, great suction gradient emerges between the lower soil layer that contains smaller initial soil water content and the upper aquifer. Which makes the water velocity increases, the infiltration rate increases, soil water content rapidly grows. (3) when the infiltration of the infiltration water in the water supply device is completed, the soil water in the deeper soil layer continues to run under the seepage until the soil water content of different depths tends to be a stable value, and the value is smaller than the saturated moisture content. All of these illustrate that in unsaturated soil, when the capillary water infiltrates a period of time, the upper soil water is influenced by gravity and vertical soil capillarity, soil water will infiltrates into the soil automatically and will reach a balance within a certain time. When the water infiltration is certain, the wetting front pushes a certain distance. The soil water content of some point of

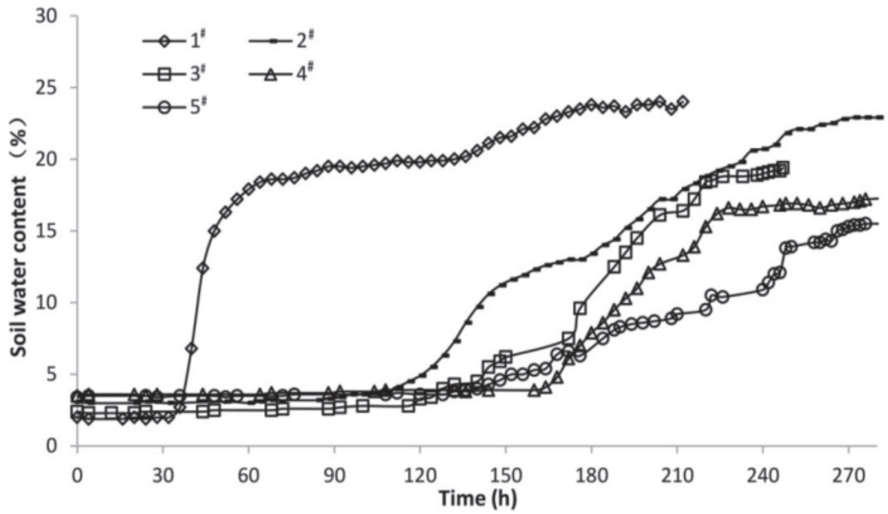

Fig.4: Soil water content change curve of monitoring point

wetting body in different soil layers will reach a stable value, which marks the water supply rate and lower upper row rate of water of the point are equal. The stable value is related to the distance from the point to infiltration point.

For a more intuitive response of the stage that soil water content changes, we establish the general linear fitting equation of moisture content and time factors: ?=kt+b. The equation parameters of 1#–5# monitoring point are shown in Table 2.

The slope of the fitting equation reduces as the distance from monitoring points to infiltration points increases, which indicates that when the distance of infiltration point is farther, the growth rate of soil water content lower; the greater the initial soil water content is, the smaller soil water potential gradient is. And the average infiltration rate is lower, the time that infiltration rate tends to be stable is shorter (Table 2). As the soil moisture continuously increases, soil water content at 1#–5# monitoring point gradually stabilized, marking that the change of soil water content goes into the final stage. The effect of initial soil moisture content on infiltration capacity is not constant, and it gradually decreases with the extension of infiltration time, and can be ignored in the end. Soil moisture migrates from 1# monitoring point to 5# monitoring point requiring a certain amount of time. So with the deepening of depth, the rising point at the stage of rising soil water content of the next monitoring point delays compared to the previous monitoring point. Under the condition of a certain amount of infiltration water, it is shown that the migration velocity of soil water both vertically and transversely becomes slower. This shows that soil brings certain retention effect on water and has positive effect on the normal growth of crops.

TABLE 2: PARAMETERS OF SOIL WATER CONTENT FITTING EQUATION OF MONITORING POINTS

Monitoring points	1#	2#	3#	4#	5#
k	0.885	0.1705	0.1332	0.1091	0.0849
b	-28.3	-14.692	-12.594	-10.3586	-8.1232
R2	0.9563	0.9604	0.9721	0.9775	0.9828

3.3 ANALYSIS OF SOIL WATER THERMAL COUPLING MOTION CHARACTERISTICS

We can see the temperature and time curve monitored by 1#–5#TDR monitor from Fig.5. As is shown in Fig.5, the temperature of soil change regularly as time extends under the condition of capillary source water supply. In general, the temperature change is mainly divided into 2 stages of heating and cooling in a day. The stage of healing is from 7 am. To 5 pm, which last about 10 hours. The stage of cooling is from 5 pm. to 7 am., which lasts about 14 hours. The lowest value in the day is at around 7 am., the highest value is at around 5 pm. After 32 hours of capillary water infiltration, soil moisture migrates to 1# monitoring point. Compared to the temperature of soil at the 1#–4# monitoring point in the same period, we can see that the 1# monitoring point rise of soil temperature slows and falling accelerates as the water content increases. The highest temperature in one day was the lowest among 5 monitoring points, and the other monitoring points had similar changing regularity to 1#. From August 10th to 14th,the environment temperature is 22-35ºC, which is significantly lower than the lowest soil temperature and higher than the highest soil temperature. And the extreme value distribute before the soil temperature. All of these explain that the soil temperature change depends on the change of air temperature, soil water content increases with the

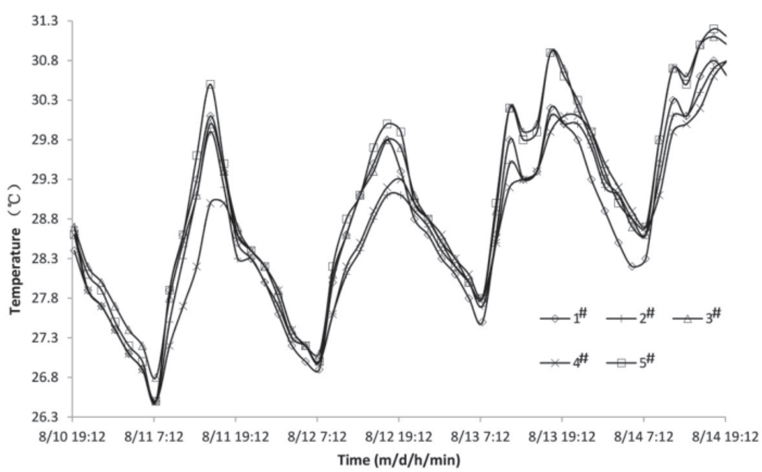

Fig.5: Temperature changes with time

migration of soil water, which will lead to the increasing of soil heat delivering. And the temperature conductivity amplifies with the amplifying of heat conductivity [13], which makes soil temperature at the 1# monitoring point (being embedded shallower) be lower than the temperature at other points.

The temperature changes affect water viscosity, density, surface tension and other physical properties [14]. The change of kinematic viscosity will act on the kinetic energy of water, and the change of soil surface tension and soil structure properties mainly affect the potential energy of soil moisture, and the two aspects interact [15]. At the same time, temperature and temperature gradient in turn influence the infiltration movement of capillary water. The movement of water brings the heat or absorbs heat to affect soil temperature. Utilizing the relationship between temperature and humidity to ensure that the plants not to grow in high temperatures during the day, and cool the plants, so that the plants can grow normally. At night, the atmospheric temperature decreases, which is not conducive to the growth of plants. But the time that soil temperature reduces lags, so it makes the growth of plants avoid the adverse external environment, which guarantee the growth of plants. The bottom of the water supply device is placed on the soil surface, which reduces the evaporation of soil water controls the soil surface temperature, and makes the soil surface temperature and humidity change without affecting the relationship between temperature and humidity. In the tillage layer, soil temperature change is mainly affected by the ambient temperature. The keep of temperature is conducive to the physiological needs of the crops, water supply device strengthen the heat preservation performance of soil by using capillary water source, which is very important for the seedling cultivation and seedling emergence.

3.4 Wetting front migration characteristics

When the amount of capillary infiltration is 3L, 8L and 12L, the distribution of soil moisture content and the distance Rf from the capillary source infiltration point is shown in Fig.6. It can be seen from the figure that under a certain amount of infiltration water, the moisture content at the capillary infiltration point is a certain value. The volume of wetting body depends on the amount of infiltration. When the infiltration amount is large and the distance of transporting soil water is far, the wetting body is big and vice versa. When the infiltration amount is 17L and t=240h, soil water content in vertical and horizontal direction are inconsistent and the wet front puts forward like a half ellipsoid (Fig.7).

3.5 Wetting simulation

3.5.1 Shape simulation

Zhao Weixia and her partners [9] introduce the concept of wetted body field when they do the non-pressure irrigation experiment, and they think that the soil moisture content around the emitter is lower than the saturated moisture content. When supply water, the volume of infiltration is small for the controlling of cloth's capillary action. Especially the infiltration amount is very small when the infiltration rate tends to be stable. The soil water content at the capillary water outlet point of soil moisture is less than the total water saturation ratio. Capillary water shows a situation of unsaturated inflow infiltration in the whole infiltration process. The tested soil is sieved within a spec of 1.5*1.5cm. The size of particle is uniform, the initial moisture content is similar. Therefore, it can be considered that the soil water content conforms to the imaginary setting of equivalent surface field under the condition of capillary source water supply. In the process of soil water infiltration, the main driving forces are the capillary force and gravity because the gaps among pores are small and they are plugged by the cloth. When the seepage time is certain, the vertical force is slightly stronger than the lateral force, which makes the migration distance of the wetting front in the horizontal plane (x0y) shorter than the vertical wetting front migration distance, and the shape is semi ellipsoidal. We can know from the section of wetting body, the curve of wetting front advances like semi elliptic curve. X, Z are coordinate points on the wetting front curve, Xf is the horizontal pushing distance and Zf is vertical pushing distance of wetting front. The equation is represented as the points on the curve of

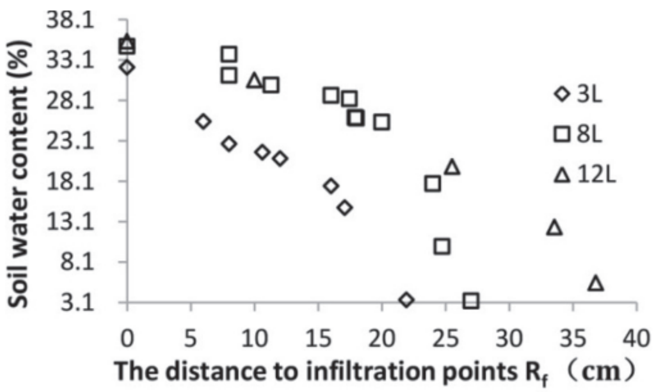

Fig.6: Distribution of soil moisture content and Rf scatter point

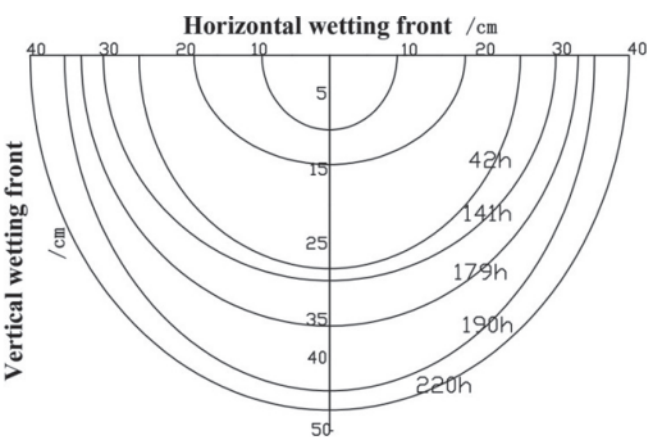

Fig.7 Contour line distribution of soil moisture content t=240h

wetting front. Using the measured data, we can obtain that Xf and Zf linear are correlated, as is shown in Fig.8a. At the initial stage of infiltration, the amount of infiltration water is very small, and the stable value cannot be formed. The soil water content is too little to satisfy the needs of water for plant growth, and there is no practical significance. When Q>3L, we can know that Q is linear with the advancing distance of longitudinal wetting front. Zf=kQ+c, as is shown in Fig.8b.

The shape simulation equation is derived as follows:

$$\frac{x^2}{X_f^2} + \frac{z^2}{Z_f^2} = 1 \qquad ... (1)$$

$$Z_f = aX_f + b \qquad ... (2)$$

$$Z_f = kQ + c \qquad ... (3)$$

Bring type (3) into the type (2), we can know:

$$X_f = \frac{kQ+c-b}{a} \qquad ... (4)$$

Bring type (3), (4) into type (1), we can know:

$$a^2x^2 + z^2 = (kQ + c_1)^2 \qquad ... (5)$$

Using the fitting parameter values in Figure 8, the equation of wetting body shape can be obtained:

$$[1.2x^2 + z^2 = (1.2Q + 18)^2] \qquad ... (6)$$

3.5.2 Model verification

Every time we finish the infiltration experiment, we excavate the wetting body along the central axis, measure the corresponding test index, and use the implementation of 3D coordinate measure the pushing distance of wetting front (coordinates). The verification results show that numerical values of left and right ends of the equation $[1.2x^2 + z^2 = (1.2Q + 18)^2]$ differs from each other at 2-3 cm as for different coordinates. And the deviation is relevant to the distribution of capillary source on the surface of soil. For a given amount of water, the equation has some practicality. It can be seen that the size and shape of wetting body have no relation with infiltration time, mainly depend on the volume of infiltration. When water is certain, can according to the infiltration amount for the wetting front

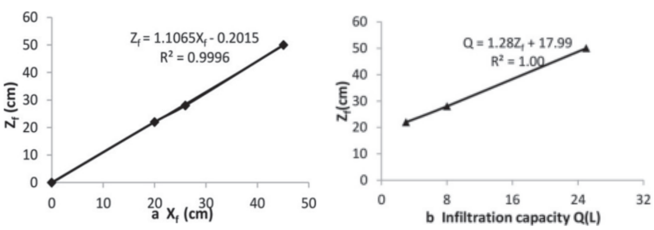

Fig.8: Curves of pushing distance of wetting front from Xf to Zf and relationship between infiltration capacity and Zf

migration position. The model has guiding significance for the normal growth of crop roots in soil and the growth of crops, and can further improve the water supply device according to the model to achieve the goal of saving water efficiently.

4.0 Conclusion and suggestion

(1) This paper reveals the water supply mechanism of capillary source. When the household cloth is completely soaked in water, the strips of cloth are laid on the surface of soil so that they can fully contact with soil particles. Then there exists gradient of soil water potential, water in the strips of cloth is absorbed by soil, and defuses all around as a semi oval. When water in the cloth reduces, pores of sloth open, water supply device continuously supply cloth with water, then soil particles near the cloth continue to absorb water and spread outwards. Such circulations realize the water-saving irrigation.

(2) There is a power function relationship between the cumulative infiltration quantity and time under the condition of water supply of surface capillary.

(3) In the process of infiltration, soil moisture content of the soil in any depth usually experience four phases---stability, sharp rise, slow increase and stability. The length of time each phase experiences is relevant to soil density, initial moisture content, permeability, soil temperature and depth of the ground. Starting from the actual shape of wetting body in the test, we can construct three-dimensional equation of wetting body, and can roughly ascertain the transferring position according to the water yield, which has referential significance to planting corps.

(4) In the soil moisture movement, water viscosity coefficient and water vapor diffusion are affected by soil temperature. And changes of soil temperature directly affect retention and movement soil moisture. When soil temperature is high, the gradient of soil water potential is large, the speed of wetting front and the infiltration rate are high. Effect of soil temperature on the rate of soil wetting front movement and the rate changing of water infiltration changes along with the change of the temperature. The impact is more obvious in low temperature region than in high temperature. But there is no clear boundary between low temperature and high temperature area, their difference is about 30?. The first main factor which affects the soil is air temperature, the second one is soil water content. Soil temperature and soil moisture affect each other, and the infiltration situation is complex.

(5) The cloth on the bottom of the water supply device can slowly transport water to soil, providing enough water for the plant growth for the first year. but it still keeps the roots dry enough to make the seedling roots dip into soil. At the same time, the device prevents soil water from evaporating, so as to improve the efficiency of water use, effectively enhance the ability to resist the high surface temperature, wind, animal browsing and other threats and damages in the seedling desertification area, slow down the

surface moisture dissipation and other functions within micro environment of the mainland, and create suitable environment for the normal growth of seedlings. The device developed in this paper needs a small scale of investment, and it is simple in structure and rich in series products. It can adapt to all kinds of complicated and changeable environment conditions and it functions well.

(6) Soil water infiltration has many factors, it is not only affected by rainfall intensity, duration and other external conditions, the characteristics of the soil itself is the main factor affecting infiltration performance. Although there are significant differences in soil infiltration capacity under different land use patterns, topography and geomorphic sites, the nature of these differences is the soil itself or surface crust. One study suggests that soil infiltration capacity mainly depends on the soil mechanical composition, water stable aggregates, soil density, organic matter content and soil initial moisture content: texture thick, stronger permeability; the more the content of water stable aggregates is greater than 0.25mm, the steady infiltration rate is bigger; the smaller the density, infiltration the capability of the organic matter; more infiltration capacity is better; the initial soil water content is larger and the infiltration capacity is smaller, and the effect of soil water content on infiltration is mainly reflected in the early infiltration. Although the soil infiltration performance is affected by its various characters, but the influence degree of each factor has bigger difference.

(7) This paper provides scientific basis for the research and development of simple devices with low cost, high efficiency, water saving, planting and irrigation. The utility model can provide water for plants, and the plants can survive and grow normally in the reservoir falling zone, the shrub zone, the rock surface, the mountain area, the desert or any other difficult area.

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