

Effects of alternate moistube-irrigation on soil water infiltration

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Abstract: Alternate moistube-irrigation is a new type of water-saving irrigation, and research on water infiltration with alternate moistube-irrigation is important for the design of irrigation schemes and helpful to understand and apply this technology. The effects of the pressure head (1.0 m and 1.5 m) and tube spacing (10 cm, 20 cm, and 30 cm between two moistubes respectively) on soil water infiltration in alternate moistube-irrigation were studied in laboratory experiments, and the cumulative infiltration, discharge of the moistube, and shape and water distribution of the cross-section of the wetting front were determined. The cumulative infiltration increased quickly and linearly with the infiltration time at 0-96 h ($R^2 > 0.99$), and changed smoothly at 96-192 h with a basically steady infiltration rate. The discharge of the moistube increased rapidly at the beginning of irrigation, then decreased before stabilizing. The cumulative infiltrations and discharges of moistube under the 1.5 m pressure head were more than those under the 1.0 m pressure head. The shape of the cross-section of the wetting front for a single moistube was similar to a concentric circle. With the increase of tube spacing, the interaction between water infiltrations of two moistubes decreased. The soil water distributions around two moistubes were similar to each other under the 1.0 m pressure head and large tube spacing. When the tube spacing was 20 cm, the soil water distribution was more uniform around two moistubes.

Keywords: alternate irrigation, moistube-irrigation, soil water infiltration, water use efficiency, water-saving irrigation

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1 Introduction

The shortage of freshwater resources has become a bottleneck of-restricting agricultural development and global food security^[1-4]. In order to alleviate the contradiction between the shortage of freshwater resources and rising world food demand, many countries are actively developing water-saving irrigation methods^[5-7]. Moistube-irrigation, also called semi-permeable membrane irrigation, is a new type of water-saving irrigation technology that has arisen in recent years in China^[8]. Moistube-irrigation takes advantage of the special properties of semi-permeable membranes to provide timely and adequate moisture to crop root zones in a continuous flow mode so that soil is always kept moist^[9-11]. As a result of the implementation of underground continuous irrigation by means of micro and slow release, deep seepage and surface evaporation are effectively controlled, resulting in saving of irrigation water. In addition, the system only needs a low-water-pressure head and negative pressure-potential of soil water to operate, thereby also saving energy. At present, Moistube-irrigation is gradually being promoted and applied to production in China^[12-15]. The research on moistube-irrigation now mainly includes two aspects: soil box simulation test and plant cultivation test. The soil box simulation

test mainly focuses on the effects of pressure head, soil texture and bulk density on the characteristics of the wetting body front, the outflow and anticlogging performance of the tube^[10,11]. The plant cultivation test mainly focuses on the effects of pressure head, buried depth and spacing of tubes on crop growth and yield^[13-15]. However, most researches currently focus on conventional continuous irrigation, and researches on other irrigation modes are relatively rare.

As early as the 1970s, alternate row irrigation or alternate furrow irrigation was attempted for some crops. Since the 1990s, some scholars have thoroughly studied the principle of plant root signals under water stress, providing a theoretical basis for alternative irrigation^[16-19]. Controlled alternate partial root-zone irrigation technology is a water-saving irrigation technology that can not only satisfy crop water demand but also control ineffective transpiration. It can reduce plant transpiration and ineffective evaporation of soil moisture by irrigating part of the root zone alternately during some or all growth stages of crops, while other root zones are under artificial water stress, so as to save water and improve water use efficiency. At present, many studies on alternate furrow irrigation^[20-24] and alternate drip irrigation^[25-29] have been carried out on many crops. Wei et al.^[30] reported that, compared with conventional moistube-irrigation, the alternate moistube-irrigation with a watering interval of 2 d significantly improved tomato water use efficiency without significantly reducing the fruit yield. The reason was that the alternate moistube-irrigation stimulated a compensating effect on tomato root absorbency, and enhanced the ability to absorb soil water. However, research on the combination of moistube-irrigation and alternative irrigation is rare, and research on the infiltration and migration of soil water under alternative moistube-irrigation is still scarce.

The objective of this study was to determine the effects of the

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pressure head and tube spacing on cumulative infiltration, discharge of the moistube, and the shape and water distribution of the cross-section of the wetting front in alternate moistube-irrigation through laboratory experiments.

2 Materials and methods

2.1 Experimental details

The experiments were carried out in the College of Water Conservancy and Engineering, Taiyuan University of Technology, China from March to June in 2018. The equipment used in the laboratory experiment (presented in Figure 1) includes a Mariotte bottle, moistube pipe, water delivery pipe, soil box, and movable bracket. Two Mariotte bottles were used to maintain constant pressure head, and different pressure heads were produced by the Mariotte bottles placed on an adjustable height bracket. Two water delivery pipes of black polyethylene (PE) with inner diameters of 16 mm were connected to the Mariotte bottle and moistube pipe. Water supply was controlled by installed valves, and alternate moistube-irrigation was carried out by opening and closing the valve at different times. The water used in the experiment was filtered urban tap water. The moistube pipe was 1 m long with an inner diameter of 16 mm, and a wall thickness of 1 mm. The moistube pipe was produced by Shenzhen Moistube Irrigation Co., Ltd. The soil box was made of transparent plexiglass and was 100 cm×40 cm×40 cm (length, width, and height). Holes with different spacing distances (10 cm, 20 cm, and 30 cm) in both short side panels of the soil box were used to accommodate the moistube pipe, and the short side panels of the soil box were detachable. Samples of clay loam soil were evenly mixed and screened by a 2 mm sieve after drying and rolling. As determined by an MS 2000 laser particle size analyzer, the particle size ranges of $d \leq 0.002$ mm, $0.002 < d \leq 0.02$ mm, and $0.02 < d \leq 2$ mm were 23.30%, 40.58%, and 36.12%, respectively. The soil bulk density was set at 1.3 g/cm³, and the initial soil water content was 1.38%.

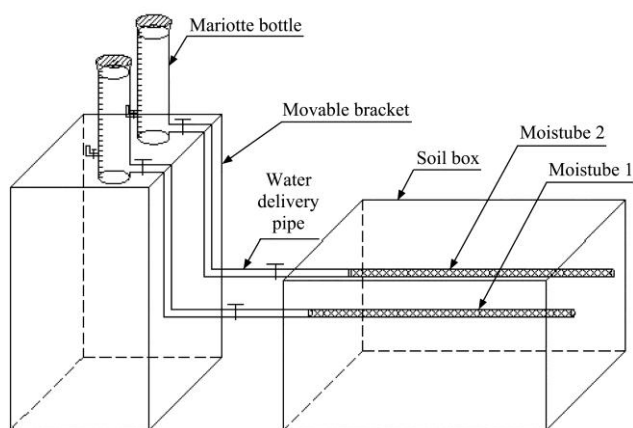


Figure 1 Experimental setup

2.2 Treatments and measurements

Treatments in the laboratory experiment consisted of the factorial combinations of (i) two pressure heads of 1 m and 1.5 m (H1 and H2), and (ii) three tube spacings of 10 cm, 20 cm, and 30 cm (S1, S2, and S3). According to the required bulk density, a certain amount of soil sample was loaded into the soil box and, when the soil thickness reached 30 cm, two moistube pipes were laid horizontally with different tube spacings, and then another 10 cm of soil was loaded. Three replicates were adopted in all experiments. The water levels of two Mariotte bottles were

recorded before the start of the test, and then the valve of moistube 1 (M1) was opened to supply water. After 4 d, the valve of M1 was closed, and then the valve of moistube 2 (M2) was opened to supply water for another 4 d. The total testing times for each of the treatments of H1S1, H1S2, H1S3, H2S1, H2S2, and H2S3 were 8 d. The total testing time for each of the treatments of H1S2-2 and H2S2-2 was 16 d, with the valves of M1 and M2 opened and closed a second time for another 4 d. For the first 12 h of water supply, the water level of the Mariotte bottle was recorded every 2 h, and then the water level was recorded every 12 h. Cumulative infiltration and the discharge of the moistube were calculated according to the time period. The wetting front position on both sides of the soil box was drawn, and the shape of the cross section of the wetting front was depicted with AutoCAD. Soil water contents in the cross section of the wetting front were measured by a drying method at the end of the test. The short side panel of the soil box near the end of the moistube pipe was removed, and soil samples were taken from the soil cross section to determine the soil moisture content. Soil sampling points were 5 cm, 10 cm, 15 cm, 20 cm, 25 cm, 30 cm, and 35 cm longitudinally from the surface of the soil cross section, and 5 cm, 10 cm, 15 cm, 20 cm, 25 cm, 30 cm, and 35 cm horizontally from the left side (near M1) of the soil cross section.

2.3 Data analysis

Analysis of variance was performed to determine the effect of alternate moistube-irrigation on cumulative infiltration and discharge of the moistube using Tukey's Honest Significant Difference (HSD) test. Statistical analysis was performed using IBM SPSS Statistics version 20.0 (IBM Corporation, Somers, New York).

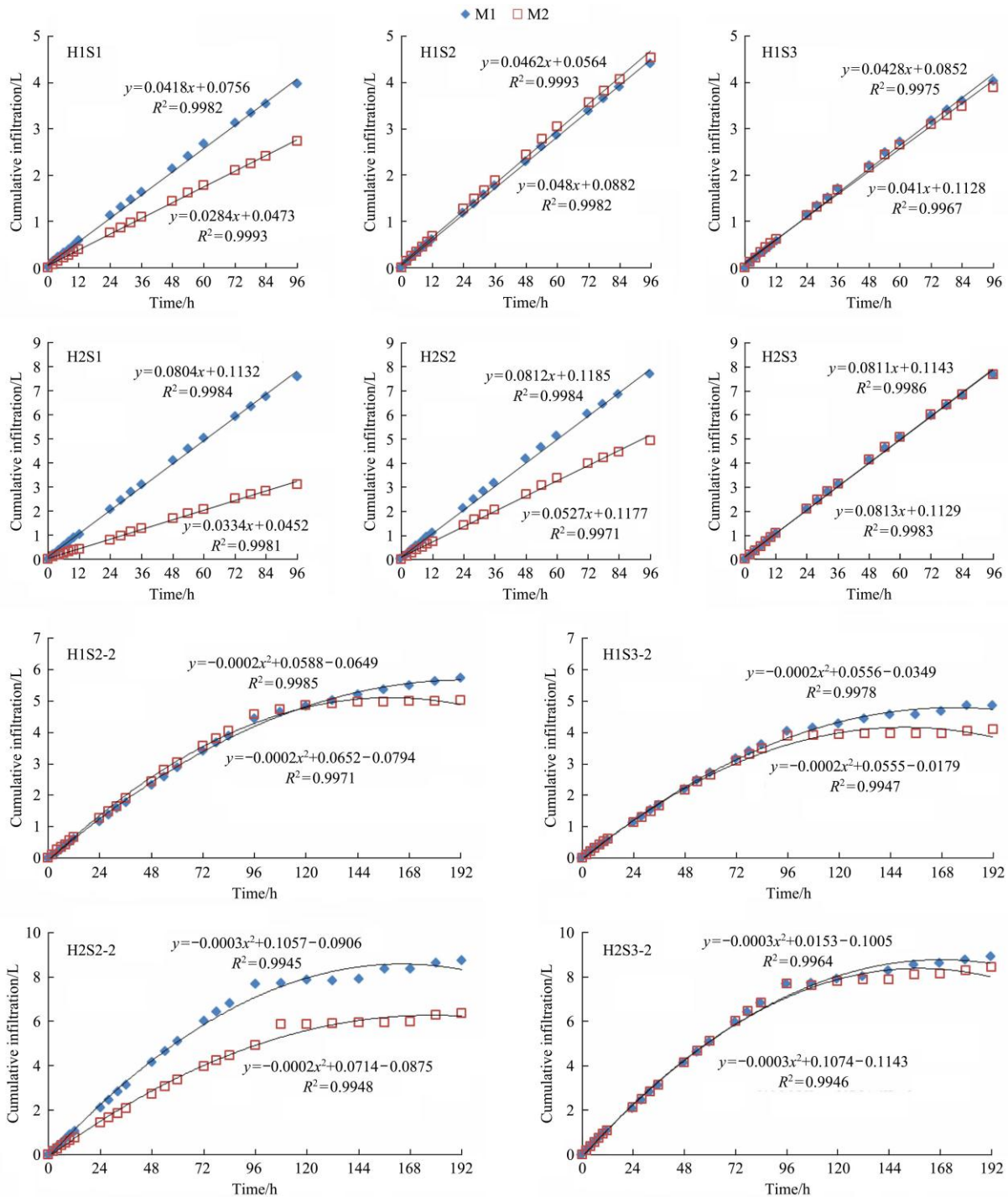
3 Results and discussion

3.1 Cumulative infiltration

Cumulative infiltration under different pressure heads and tube spacing in alternate moistube-irrigation is shown in Figure 2. The cumulative infiltration of M1 and M2 increased linearly with the infiltration time at 0-96 h ($R^2 > 0.99$). Pressure head was an important factor affecting water infiltration: the greater the pressure head, the greater the cumulative infiltration. The cumulative infiltration of M1 and M2 under the 1.5 m pressure head was significantly more than that under the 1.0 m pressure head ($p < 0.05$).

For the treatments of H1S1, H2S1, and H2S2, the cumulative infiltration of M1 was significantly more than that of M2 ($p < 0.05$), while for the treatments of H1S2, H1S3, and H2S3, the cumulative infiltration of M1 was nearly equal to that of M2. When the tube spacing was S1, the soil wetting front of M1 had moved to the vicinity of M2 before M2 began to supply water, thus the cumulative infiltration of M2 was low due to high soil water content. When the tube spacing was S2, the soil wetting front of M1 migrated a small distance under the 1.0 m pressure head, which had little effect on M2, but under the 1.5 m pressure head, the soil wetting front of M1 migrated a large distance, thereby affecting the infiltration of M2. When the tube spacing was S3, the infiltrations of M1 and M2 had little effect on each other.

The cumulative infiltration of M1 and M2 increased with the infiltration time quickly at 0-96 h, and changed smoothly at 96-192 h with a basically steady infiltration rate. At 0-192 h, the relationship between the cumulative infiltration of M1 and M2 and infiltration time can be expressed by a polynomial equation ($R^2 > 0.99$).



Note: H1 and H2 represent pressure heads of 1.0 m and 1.5 m; S1, S2, and S3 represent tube spacing of 10 cm, 20 cm, and 30 cm; M1 and M2 represent moistube 1 and 2; y represents the cumulative infiltration and x represent the infiltration time.

Figure 2 Cumulative infiltration in alternate moistube-irrigation

3.2 Discharge of the moistube

The discharge of the moistube under different pressure heads and tube spacings in alternate moistube-irrigation is shown in Figure 3. The discharges of M1 and M2 for the treatments of H1S1, H1S2, H1S3, H2S1, H2S2, and H2S3 increased rapidly at 0-6 h or 0-8 h, then decreased at 6-24 h or 8-24 h, and changed smoothly at 24-96 h. The discharges of M1 and M2 under the 1.5 m pressure head were significantly more than those under the 1.0 m pressure head ($p < 0.05$).

For the treatments of H1S1, H2S1, and H2S2, the discharges of M1 were significantly more than those of M2 ($p < 0.05$), while for the treatments of H1S2, H1S3, and H2S3, the discharges of M1 were nearly equal to those of M2. When the tube spacing was S1

or S2, the difference between the discharges of M1 and M2 under the 1.5 m pressure head was larger than that under the 1.0 m pressure head. For the treatments of H1S2-2, H1S3-2, H2S2-2, and H2S3-2, the discharges of the moistube at 96-192 h were lower than those at 24-96 h, as the soil was wetter when the moistube began to supply water the second time than before irrigation.

The discharge of the moistube increased rapidly at the beginning of irrigation, then decreased and remained at a stable level as time elapsed. There was an induction period that was probably within 24 h from the start of moistube-irrigation, and discharge of the moistube remained stable after 24 h of irrigation. Niu et al.^[31] reported that the moistube had a weak and short duration of self-regulated flow with changes in soil moisture

content at approximately 44 h, and the flow increased quickly and then decreased to a steady state after 48 h of irrigation. The difference of the time needed for the stable discharge of the

moistube may be related to the pressure head, soil bulk density, soil texture, soil initial water content, and/or different test conditions.

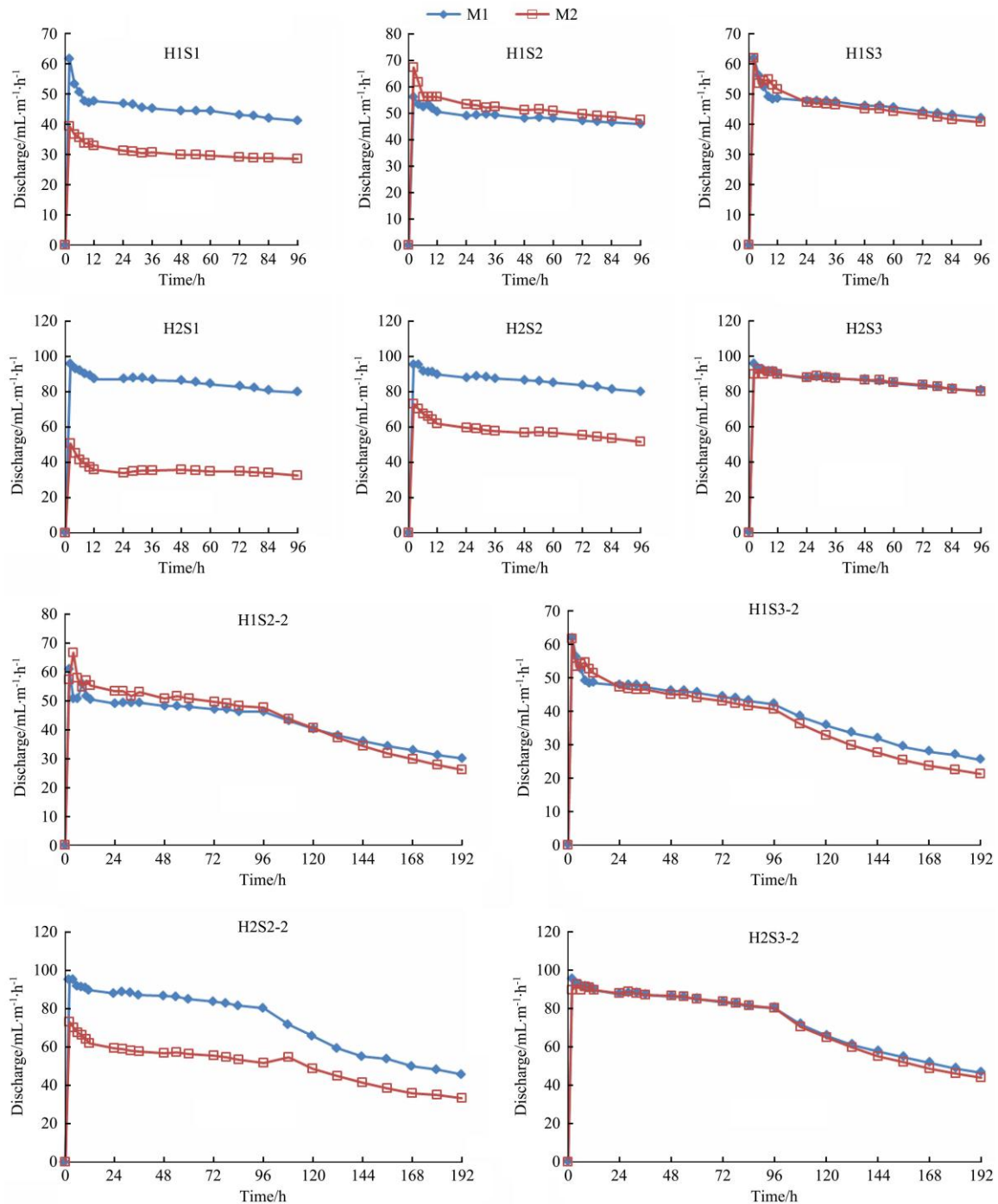


Figure 3 Discharge of the moistube in alternate moistube-irrigation

3.3 Shape of the cross-section of the wetting front

The shape of the cross-section of the wetting front under different pressure heads and tube spacings in alternate moistube-irrigation is shown in Figure 4. The shape of the cross-section of the wetting front for a single moistube was similar to a concentric circle, and the area of the cross-section of the wetting front under the 1.5 m pressure head was larger than that under the 1.0 m pressure head. The wetting fronts of M1 and M2 were superposed when the tube spacing was S1, were a little superposed when the tube spacing was S2, and did not affect each other when the tube spacing was S3. Zhang et al.^[32] reported that wetted soil with moistube-irrigation looked like a cylindrical object,

with the pipe at the axle center of its cross section, which for clay loam soil was approximately cylindrical, and for sandy soil was of obpyriform shape. The same result for clay loam soil was obtained in this experiment.

3.4 Water distribution in the cross-section of the wetting front

Figure 5 shows the water distribution in the cross-section of the wetting front in alternate moistube-irrigation at the end of the test. For the treatments of H1S1, H1S2, H2S1, and H2S2 in which the test ended in 8 d, the soil around M2 had higher water content than that far away from M2 as the water supply from M2 had just finished, and the water migrated longer distances under the 1.5 m pressure head than under the 1.0 m pressure head.

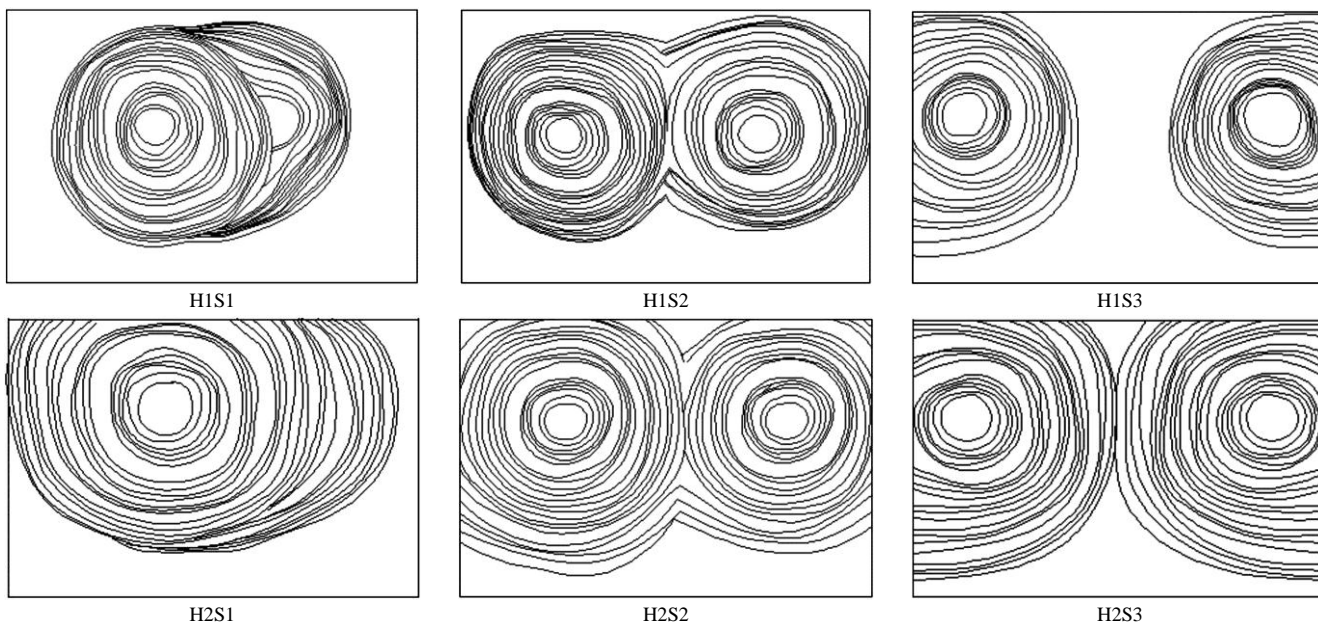
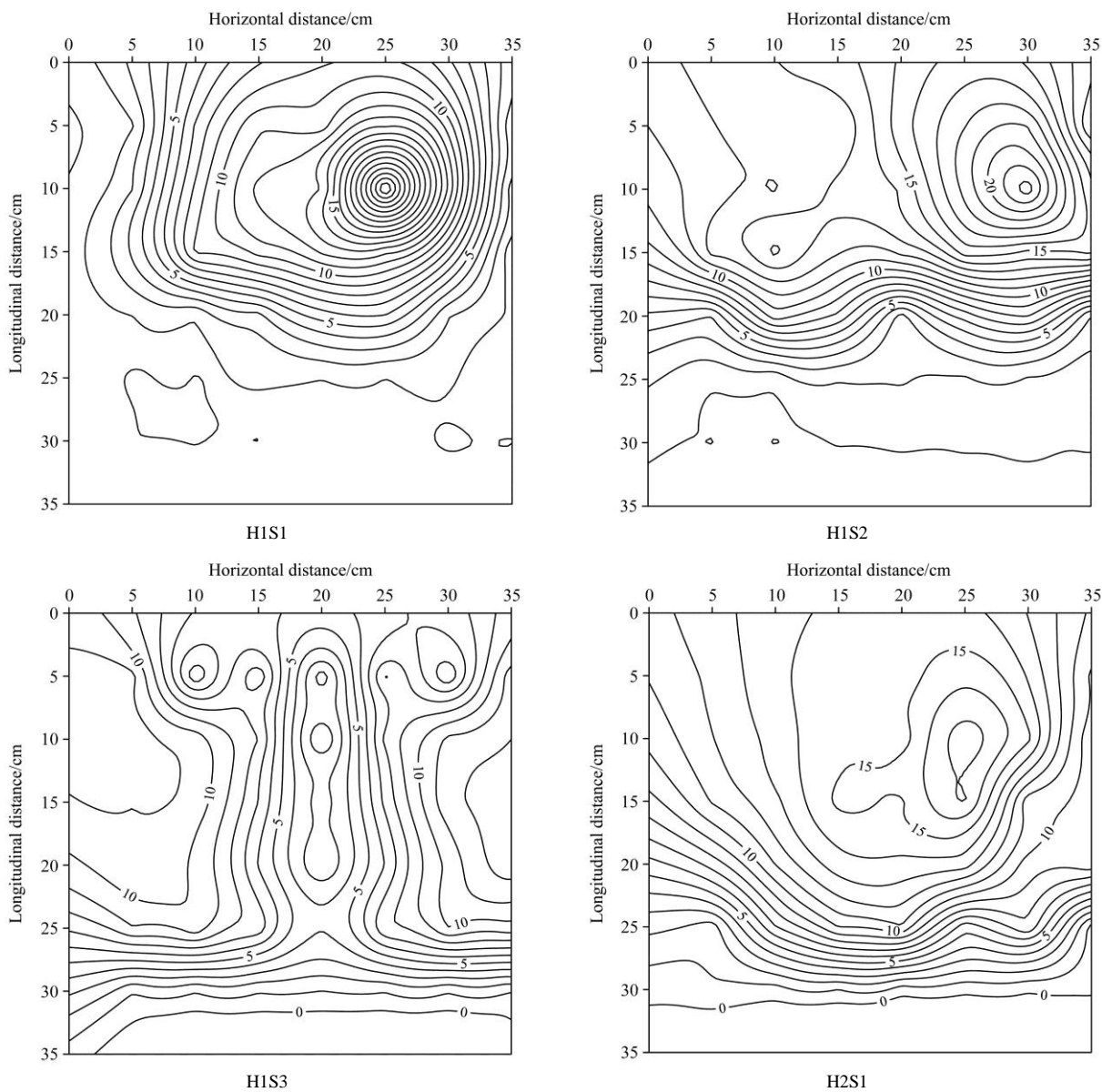


Figure 4 Shape of the cross-section of wetting front in alternate moistube-irrigation



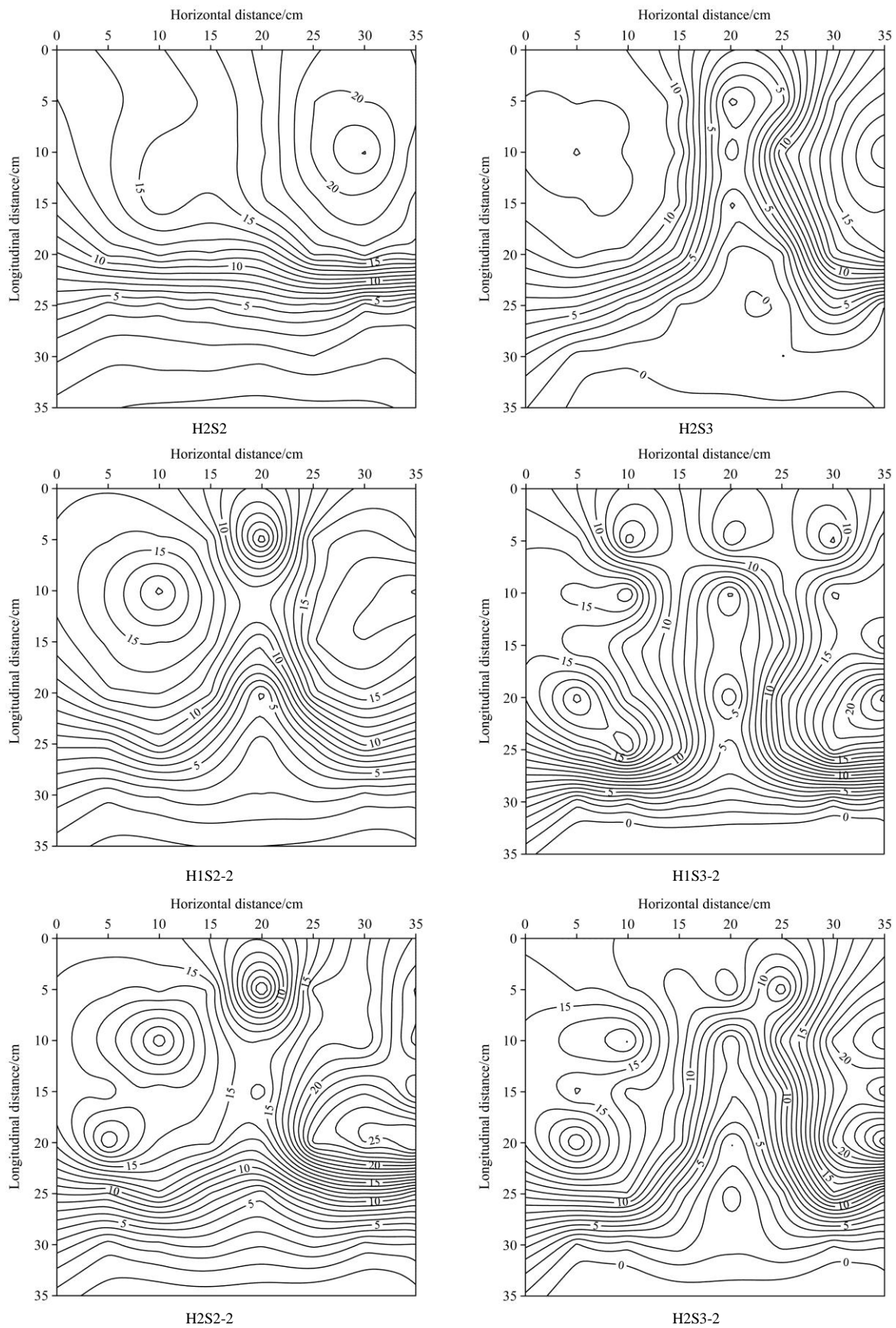


Figure 5 Water distribution in the cross-section of the wetting front in alternate moisture-irrigation at the end of the test

For the treatment of H1S3, the soil water distributions around M1 and M2 were similar to each other, as water supplies from M1 and M2 did not affect each other under the pressure head of 1.0 m and the large tube spacing of S3. For the treatment of H2S3, the range of water migration was larger than that for the treatment of

H1S3 as water migrated over longer distances under the 1.5 m pressure head.

When the test ended in 16 d, the soil near M1 had higher water content for the treatments of H1S2-2 and H2S2-2 than that for the treatments of H1S2 and H2S2, and the soil water distribution was

more uniform around M1 and M2. For the treatment of H1S3-2, as for the treatment of H1S3, the soil water distributions around M1 and M2 were similar to each other, and the difference between H1S3-2 and H1S3 was that the soil had higher water content for H1S3-2. For the treatment of H2S3-2, the soil near M1 had higher water content than that for H2S3, and the water distribution range for H2S3-2 was larger than that for H2S3.

4 Conclusions

The effects of the pressure head and tube spacing on soil water infiltration in alternate moistube-irrigation were studied in laboratory experiments, and the cumulative infiltration, discharge of the moistube, and shape and water distribution of the cross-section of the wetting front were determined. With the infiltration time from 0 to 96 h, the cumulative infiltration volume of M1 and M2 increased rapidly and linearly ($R^2 > 0.99$), while from 96 h to 192 h, it changed smoothly and the infiltration rate was basically stable. Pressure head was an important factor affecting water infiltration, and the greater the pressure head, the greater the cumulative infiltration. The cumulative infiltrations of M1 and M2 under the 1.5 m pressure head were more than those under the 1.0 m pressure head. With increased tube spacing, the interaction between water infiltration of M1 and M2 decreased. The discharges of M1 and M2 under the 1.5 m pressure head were more than those under the 1.0 m pressure head. At the beginning of moistube-irrigation, the discharge of water increased rapidly, then decreased and remained at a stable level over time. The water induction period might exist within 24 h after the start of irrigation, and the water flow remained stable after 24 h of irrigation. The cross-sectional shape of the wetting front of a single moistube resembled a concentric circle. The cross-sectional area of the wetting front under the 1.5 m pressure head is greater than that under the 1.0 m pressure head. With increased tube spacing, the interaction of the wetting bodies between M1 and M2 decreased. The soil water distributions around M1 and M2 were similar to each other under the 1.0 m pressure head and large tube spacing of S3. When the tube spacing was S2, the soil near M1 had higher water content when the test ended in 16 d compared to when the test ended in 8 d, furthermore, soil water distribution was more uniform around M1 and M2.

The laboratory experiments differed in a few ways from what could be expected with actual field conditions, and the effect of alternate moistube-irrigation on plant growth should be investigated in the field.

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