STUDY ON THE SOIL MOISTURE MOVEMENT UNDER INFILTRATION IRRIGATION / 渗灌条件下土壤水分运移规律研究

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Abstract: *To explore moisture movement under infiltrating irrigation and contribute a theoretical basis for agricultural production, we carried out a laboratory simulation experiment to study soil moisture movement under different pore diameters, pressures, and bulk densities. Results showed that the wetting front of both sandy soil and loamy soil increases gradually under three hydraulic head pressures (0.02, 0.01, and 0.005 MPa) as irrigation proceeds. Viewed from the entire shape of the wetting front, the wetting front of* Ø25mm irrigation pipeline with 2.5 mm pore diameter *is uniform. Under two bulk densities (1.54 and 1.43 g·cm^{-3}), given 0.02 MPa pressure,* Ø25mm irrigation pipeline with 2.5 mm pore diameter, *the wetting front of soil rises gradually as irrigation continues. The combination of a 10-year-old root distribution system of fruit trees, 0.02 MPa head pressure, and Ø32mm irrigation pipeline with 2 mm pore diameter could meet the irrigation demand of red dates.*

Keywords: *Infiltrating irrigation; Moisture; wetting front; movement*

摘要： *为了了解渗灌这项微灌技术灌水后的水分运移情况，指导农业生产提供理论依据，为此，在室内通过土壤模拟实验模拟在不同孔径，压力，容重下土壤水分运移规律进行了研究。结果表明三种水头压力下(0.02，0.01，0.005MPa)，随着灌水时间的推移，沙土的湿润峰逐渐增加，从湿润峰的整体性状看，Φ25mm 管 2.5mm 孔径渗灌管下湿润锋的性状更加均匀，两种容重 1.54g·cm^{-3} 和 1.43g·cm^{-3} 下，在压力 0.02MPa，Φ25mm 管径 2.5mm 孔径渗灌管的情况下，随着灌水时间的推移，土壤的湿润峰均逐渐增加，结合 10 年果树根系分布状况得知，水头压力采用* 0.02MPa*，采用 Φ32mm 管 2mm 孔径的渗灌管能更好的满足红枣的灌溉需求。*

关键词： *渗灌；水分；湿润峰；运移*

INTRODUCTION

Root infiltration irrigation is a new water-saving irrigation technology that has been applied in Xin jiang's forestry and fruit industry in recent years [1,8,11]. This irrigation system has excellent anti-clogging ability and could operate normally under low pressures (2.5–20 KPa). Unlike point water outlet of micro-irrigation, root infiltrating irrigation provides a line water outlet. The root irrigation pipe has two water distribution patterns. One drains water from drainage holes on two sides of the irrigation pipe. The pore diameter generally varies between 2 and 5 mm, it is determined according to practical needs. Blocking these pores is difficult with the use of irrigation water that has been treated simply. The other distribution pattern involves draining water from water seams on two sides of the irrigation pipe. These water seams are formed by neck and trim strips [9] and [12]. Underground drip irrigation systems require strict daily operation management. Such a system has to be examined for defects and has a long maintenance time and high cost. In addition, a large flow of underground drip irrigation system easily causes ponding on the surface, thus resulting in significant evaporation loss of soil water [4]. A root infiltrating irrigation system could solve and avoid these problems. Preliminary research and applications on water and fertilizer management have been conducted Xinjiang's common wood industry based on red dates. [2,3,6]. However, no research has discussed the movement and distribution pattern of water in different types of soil under root infiltrating irrigation and analyzed shape changes of soil wetting front during

引言

根渗灌是近几年新疆特色林果业应用的新型节水灌溉技术 [1,8,11]。该渗灌系统具有优异的抗堵性能，并能在低压(2.5-20 KPa)条件下正常运行。许多微灌是点出水，而根渗灌是线出水，根灌管是经过两次分配出水，第一次是由灌管壁两边出水孔出水，孔径根据需要一般在2-5 mm，经过简单处理的灌溉水很难堵塞此孔径，第二次是由灌管两侧卡槽与压条形成的出水缝出水 [9][12]。地下滴灌系统日常运行管理要求非常严格，一旦发生故障后需要检查，维修时间长，而且费用高，此外地下滴灌系统流量较大在地表易形成积水而导致土壤水分蒸发损失大[4]，根渗灌系统很好解决和避免这些问题。目前已在新疆特色林果红枣果树等进行了初步水肥管理方面研究与应用 [2][3][6]，但缺乏有关根渗灌新技术在不同类型土壤中水分运移与分布规律，以及灌水过程中和灌水后土壤湿润体形体变化的研究，为了更好结合和服务于新疆农业生产实践， 开展不同渗管孔径，不同土壤类型情

and after irrigation. To sufficiently serve and contribute to agricultural production in Xinjiang, studying variation laws of soil wetting front under different irrigation pipe sizes, soil types, and water redistribution patterns is necessary. Optimum irrigation technical parameters were determined, which could help to provide timely and appropriate irrigation to fruit trees and improve water utilization.

In this paper, Ø25 mm was used as the capillary, and Ø32 mm was used as the branch pipe. The pipe network was paved according to the pipe network for the field test. Hence, laboratory soil box simulation was mainly based on Ø25 mm and Ø32 mm. A reasonable pipe size for infiltrating irrigation to red dates was determined through an analysis of the relationship between bulk density of differently sized pipes in different soil types and water advancing distances in soil directions, as well as the water redistribution pattern after irrigation. The test results are expected to provide a theoretical basis for improving infiltration irrigation and its practical applications.

况下土壤湿润体的变化规律以及灌水后土壤湿润体水分再分布情况的研究极为必要，通过研究得到最佳的灌溉技术参数，可以适时适量地对果树进行灌溉并提高水分利用效率。

本研究根据田间试验管网布设以Ø25mm管为毛管，Ø32mm管为支管，为此，室内土箱模拟法主要选择采用Ø25mm管Ø32mm管进行实验，通过分析不同孔径渗管在不同土壤容重和水分在土体中各个方向推进距离的关系，以及灌水停止后水分再分布规律，提出渗灌方式下适合红枣果树灌溉的合理渗管孔径，试验结果以期为完善渗灌技术及其实际应用提供理论依据。

MATERIAL AND METHOD

Test materials

Root irrigation apparatus is shown in Fig.1. Water supply is controlled by the intake pipe, water supply pipe and total intake valve. A stable-voltage water supply device (with drain valve and exhaust valve) is installed between the intake pipe and water supply pipe to keep stable outflow rate. The connected pressure regulating valve and pressure gauge are used for pressure regulating. Finally, water enters into the root irrigation pipes to irrigate farmlands.

Test materials include a soil moisture meter (with 24 probes), a water balancing box, There is a 1.8 m x 0.3m x 1m cuboid soil box which is formed by 1cm-thick steel plates on three sides and 1cm-thick glass plate on one side. The glass place is convenient for observing the wetting front. Please see Fig.2, several 0.2 m long irrigation pipelines (including Φ32mm irrigation pipelines with 2 mm pore diameter and Φ25mm pipelines with 2.5 mm pore diameter), a piece of earth hammer, a spade, a 2 mm sieve, a watering pot, a piece of plastic cloth, an aluminum box, an oven (or ethyl alcohol), a thermometer, a stopwatch, a tape, an electronic balance, some connecting pieces, and valves.

材料与方法

供试材料

根渗灌装置如图 1 所示，供水由进水管、供水管和总控水阀控制,在进水管与供水管之间安装有稳压供水装置（装有泄水阀和排气阀）以保证出水流量的稳定性,之后连接有调压阀和压力表进行调压,最后进入根渗管进行灌溉。

土壤湿度仪(含 24 个探头),恒水箱,1.8m*0.3m*1m的长方体土箱 1 个，三面为 1cm 厚的钢板，另一面为 1cm 厚玻璃板，玻璃版面便于湿润峰的观测，见图 2。0.2 m 长不同管径和孔径（Φ32mm 管 2mm 孔径,Φ25mm 管 2.5mm 孔径）组合的渗灌管若干,夯土锤,铁锹,2mm 筛,洒水壶,塑料布,铝盒,烘箱(或酒精),温度计,秒表,卷尺,电子称,连接件,阀门等。

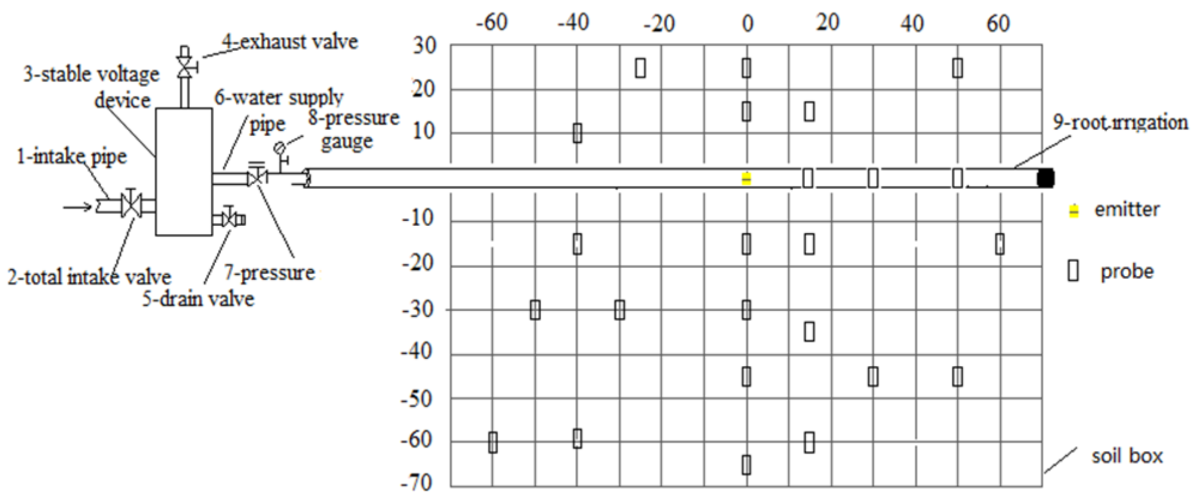

Fig. 1- Test unit

Fig. 2-Testing soil box

Test method

Sandy soils were dried and screened (pore diameter: 2 mm) and then wetted evenly by taking about 50% moisture content of field capacity as the initial soil moisture content. They were layered according to bulk density (each layer is 5 cm thick) and then tamped into the soil box. Differently sized infiltration pipes and probes were buried horizontally during soil filling according to requirements (the infiltration pipe passes through the glass plate). The infiltration pipe is 0.2 m long (with two holes) and is paved 30 cm underneath the earth's surface. Every test applies an infiltration pipe of a permeable pore diameter and constant water supply pressure. The infiltration water was measured every half hour after the test began, and the wetting front was drawn on the glass plate every 10 min (or according to practical infiltration situations). The occurrence time and size range of the saturation circle that surrounds each testing infiltration pipe (soil moisture content exceeds the field capacity) were recorded. If deep leakage occurs 80 cm below the earth’s surface, the wetting front has reached 80 cm below the earth’s surface. Irrigation shall be stopped at this moment or when water accumulation is observed on the earth’s surface. Irrigation time and volume shall be recorded.

测定方法

将沙土分别风干过筛(孔径 2mm), 然后将土按田间持水量的 50%左右的含水率作为土壤初始含水率湿润均匀, 并按容重分层(每层 5cm 厚)夯实填入土箱, 同时在填土的过程中按要求水平埋入渗管与探头(渗管穿过玻璃板), 渗管 0.2m 长(布有两孔), 埋深为 30cm, 每次试验用一种透水孔径的渗管及相应恒定供水压力进行。试验开始后每隔半个小时测量入渗水量,并每隔 10 分钟(或根据入渗情况调整时间间隔) 测定湿润峰并在玻璃板上画出。同时记录各个试验渗管周围饱和圈出现(土壤含水率超过田持)的时间及尺寸范围。如果地表以下 80cm 处土壤发生深层渗漏,则表明湿润峰到达地表以下 80cm，此时停止灌水或土壤表面出现积水时停止灌水,并记录下灌水时间及灌水量。

Test items

Variation law of the wetting front against time (including the relationship between flow per meter and pressure) under different pressures, pore diameters, and bulk densities were studied. Dynamic changes of soil moisture content were monitored by using SM 100, SM100 is a soil moisture gauge made by the United States, which is mainly used to measure soil water content. It could be connected to meteorological station and data could be read quickly through the reading gauge. The flat shape design makes it easy to be inserted into soil. Watermark water potential probe and Echo water potential probe also could be read from the reading gauge.

测定项目

在不同压力, 孔径, 容重条件下的出流情况, (包括米流量与压力关系)观察湿润峰随时间的运移情况,并采用 SM100 动态监测土壤含水率变化情况。SM100 是美国生产的土壤水分测量仪，其主要用途是测量土壤水分含量，可以连接到气象站，也可以用读数表快速读取数据。扁平形状设计可以使其容易插入到土壤当中。读数表也可以读取 Watermark 水势探头和 Echo 水分探头。

RESULTS AND ANALYSIS

Variation law of cumulative infiltration

According to the correlation analysis of pore diameter, pressure, and bulk density of sandy soil, a good linear correlation exists between time and cumulative infiltration (Table 1). Under 0,01 MPa pressure and 1.54 g/cm^3 bulk density, the mean flow in air of Ø32mm irrigation pipeline with 2 mm pore diameter is 61.6 L·(h^{-1}·m^{-1}), while the mean flow in sandy soil is 20.44 L·(h^{-1}·m^{-1}), which is 67% lower than the former. The mean flow in air of Ø25mm irrigation pipeline with 2.5 mm pore diameter is 102.96 L·(h^{-1}·m^{-1}), which is 71% higher than the mean flow in sandy soil at 29.83 L·(h^{-1}·m^{-1}). This finding reflects that a larger pore diameter is accompanied by higher water flow and larger flow losses.

Under 0.02 MPa, the water flow from the Ø32mm irrigation pipeline with 2 mm pore diameter in sandy soils with different bulk densities differs significantly. The water flow in air is 93.9 L·(h^{-1}·m^{-1}). The mean water flow from infiltration pipe under 1.54 g·cm^{-3} bulk density is 49.2 L·(h^{-1}·m^{-1}), which is 48% lower than the water flow in air. The mean water flow from infiltration pipe under 1.43 g·cm^{-3} bulk density is 62.55 L·(h^{-1}·m^{-1}), which is 34% lower. This finding indicates that lower bulk density contributes higher water flow from the infiltration pipe but smaller water flow losses in sandy soil.

Given the same bulk density and pore diameter, the mean flow in sandy soil under 0.02 MPa pressure is significantly higher than that under 0.01 MPa pressure, and the water flow loss in sandy soil under 0.02 MPa pressure is relatively smaller. No significant difference is observed between the mean flow under 0.005 MPa and 0.01 MPa pressure. However, compared with water flow in air, water flow loss in sandy soil under 0.01 MPa pressure is far higher than that under 0.005 MPa pressure.

As shown in Table 1 and Fig. 3, under different conditions (pressure, bulk density, and pore diameter), cumulative infiltration into sandy soil increases as time passes. Cumulative infiltration under low bulk density is higher than that under high bulk density, which indicates the greater water potential that surrounds the permeation irrigation pipe and higher cumulative infiltration under low bulk density. Under fixed 0.01 MPa pressure but different pore diameters, the cumulative infiltration of Ø32mm irrigation pipeline with 2 mm pore diameter is far less than that of Ø25mm irrigation pipeline with 2.5 mm pore diameter. This result implies the existence of greater water potential and higher cumulative infiltration that surrounds the Ø25mm irrigation pipeline with 2.5 mm pore diameter. Cumulative infiltration varies under different pressures, it is significantly higher under 0.02 MPa pressure than under 0.01 MPa pressure. However, cumulative infiltration under 0.01 MPa pressure is similar to that under 0.005 MPa pressure.

结果与分析

累积入渗量的变化规律

沙土条件下对于不同孔径,压力和容重条件实验数据进行相关性分析发现,时间和累积入渗量具有较好的线性相关,结果见表 1。在压力 0.01MPa 和容重 1.54g·cm^{-3} 条件下,Φ32mm 管 2mm 孔径渗灌管在空气中的平均流量为 61.6L·(h^{-1}·m^{-1}),在沙土中的平均流量为 20.44L·(h^{-1}·m^{-1}),减少了 67%,Φ25mm 管 2.5mm 孔径渗灌管在空气中的平均流量为 102.96L·(h^{-1}·m^{-1}),在沙土中的平均流量为 29.83L·(h^{-1}·m^{-1}),减少了 71%,说明孔径大,出水流量大,但是损失的流量也大。

在压力 0.02MPa,Φ32mm 管 2mm 孔径渗灌管情况下,不同容重沙土中渗灌管出水流量出现很大差异性,在空气中出水流量为 93.9L·(h^{-1}·m^{-1}),在容重 1.54g·cm^{-3} 条件下,渗灌管出水平均流量为 49.2L·(h^{-1}·m^{-1}),减少了 48%,在容重 1.43g·cm^{-3} 条件下,渗灌管出水平均流量为 62.55L·(h^{-1}·m^{-1}),减少了 34%,说明低容重条件下渗灌管出水流量大,在沙土中出水流量损失较小。

在容重和孔径相同的情况下,压力 0.02MPa 在沙土中的平均流量明显大于 0.01MPa 压力,且压力 0.02MPa 下出水流量损失也小于压力 0.01MPa,压力 0.005MPa 下平均流量与压力 0.01MPa 相比较,在沙土中两个压力下渗灌管平均流量相差不大,然而与空气中流量比较压力 0.01MPa 在沙土中渗灌管流量损失要远远大于压力 0.005MPa。

从表 1 和图 3 得知,在不同条件下(压力,容重,孔径)沙土的累积入渗量随着时间的推移而增大,不同容重条件下低容重的累积渗水量要高于高容重,说明在低容重条件下渗灌周围的水势较大,累积的渗水量就高。在 0.01MPa 压力情况,不同孔径条件下,Ø32mm 管孔径 2mm 渗灌管的累积入渗量明显小于 Ø25mm 管 2.5mm 渗灌管,说明 Ø25mm 管 2.5mm 渗灌管周围的水势较大,累积的渗水量就高。不同压力条件下,压力 0.02MPa 累积入渗量明显大于压力 0.01MPa,而 0.01MPa 压力累积入渗量与 0.005MPa 压力累积入渗量相差不大。

Table 1

Fitting results of time and cumulative infiltration in sandy soil

Pressure (MPa)	Pore diameter (mm)	Bulk density(g·cm^{-3})	Mean flow L·(h^{-1}·m^{-1})	Flow in air L·(h^{-1}·m^{-1})	Fitting formula	Determination coefficient(R^2)
0.01	2	1.54	20.44	61.6	y=0.0702x - 0.1483	0.959
	2.5	1.54	29.83	102.96	y= 0.0956x + 0.8719	0.979

Pressure (MPa)	Pore diameter (mm)	Bulk density(g·cm^{-3})	Mean flow L·(h^{-1}·m^{-1})	Flow in air L·(h^{-1}·m^{-1})	Fitting formula	Determination coefficient(R^2)
0.02	2	1.54	49.2	93.9	y = 0.1565x + 1.292	0.949
	2.5	1.43	62.55	93.9	y= 0.0956x + 0.8719	0.959
0.005	2.5	1.54	29.18	71.8	y= 0.0946x + 0.6366	0.969

Note: y is the cumulative infiltration (L), and x is the corresponding time.

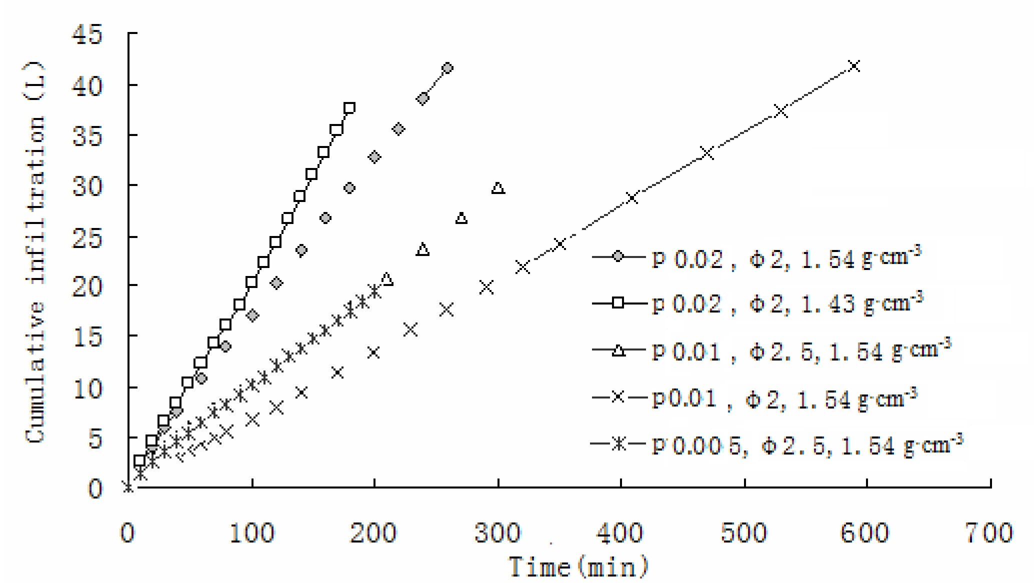

Fig. 3 - Cumulative infiltration into soil

Effect of pressure on soil moisture movement and wetting front

Effect of pressure on soil water movement and wetting front when using Ø32 mm irrigation pipelines with 2 mm pore diameter

During the laboratory simulation, irrigation pressure is a key influencing factor of the wetting front form when texture, bulk density, and pore diameter are fixed. In this paper, the dynamic changes of the wetting front form after 4 h of permeation irrigation using the Ø32 mm irrigation pipelines with 2 mm pore diameter (pressure: 0.02 and 0.01 MPa) were observed (Fig. 4).

The graph on the left shows the wetting front under 0.01 MPa pressure, and the graph on the right is the wetting front under 0.02 MPa pressure. As irrigation continued, the wetting front of the soil increased gradually. However, it changed at different rates in the horizontal, upward, and downward directions. Under 0.02 MPa pressure, the horizontal and downward changes were obviously quicker than the upward change. After 4 h, the upward, horizontal, and downward infiltration diffusion lengths were 30, 46.75, and 50.5 cm, respectively. Under 0.01 MPa pressure, the wetting front changed more quickly in the downward direction than that in the horizontal and upward ones. After 4 h, the upward, horizontal and downward infiltration diffusion lengths were 21.35, 31.22, and 36.69 cm, respectively. Infiltration in different directions under 0.02 MPa pressure is quicker than 0.01 MPa that was 28%, 33%, and 26% higher in the upward, horizontal, and downward directions. This finding means that the infiltration rate under 0.02 MPa pressure is far higher than that under

压力对土壤水分运移和湿润体的影响

在 Φ32mm 管、孔径为 2mm 组合的渗灌管下，压力对土壤水分运移和湿润体的影响

在室内模拟过程中，在质地，容重和孔径一定时， 灌溉时的压力大小是影响湿润峰形态的一个关键因子。本试验采用 Ø32mm 管孔径 2mm 渗灌管在两种压力(0.02MPa, 0.01MPa)的情况下，在试验灌水过程对湿润体在沙土中形态变化进行了 4 小时动态观测，其变化见图 4。由图 4 可看到，图的左半边为压力 0.01MPa 灌溉下湿润峰，右半边为压力 0.02MPa 灌溉下湿润峰，随着灌水时间的推移，土壤的湿润峰逐渐增加，但在水平，向上，向下各个方向上的湿润峰变化速度各不相同，在 0.02MPa 压力下，水平方向和垂直向下的方向要明显快于向上方向的湿润峰，4 h 后向上的入渗扩散距离为 30 cm，水平方向为 46.75cm，垂直向下方向为 50.5cm，在压力 0.01MPa 情况的下湿润峰向下的运移的速率高于水平方向和向上方向，4h 后向上的入渗扩散距离为 21.35cm，水平方向为 31.22cm，垂直向下方向为 36.69cm，压力 0.02MPa 孔径情况下个方向上的入渗速度均比压力 0.01MPa 情况下的快， 向上增加了 28%，水平方向增加了 33%，向下方向增加了 26%，说明 0.02MPa 压力下的入渗速

0.01 MPa pressure.

The movement distance of the wetting front increases with time, which shows a good correlation.

The fitting results are as follows:

Upward:

率显著高于 0.01MPa 压力情况下。润峰峰运移距离随时间增加而逐渐变大，两者具有较好的相关性，拟合结果如下:

向上：

$$L_1 = 9.26Ln(t) - 30.11 \qquad R^2 = 0.996 \tag{1}$$

$$l_1 = 8.41Ln(t) - 14.51 \qquad R^2 = 0.9974 \tag{2}$$

Downward:

向下：

$$H_1 = 19.69Ln(t) - 69.93 \qquad R^2 = 0.99 \tag{3}$$

$$h_1 = 12.70Ln(t) - 21.43 \qquad R^2 = 0.99 \tag{4}$$

Horizontal:

水平：

$$R_1 = 14.74Ln(t) - 49.49 \qquad R^2 = 0.98 \tag{5}$$

$$r_1 = 11.64Ln(x) - 20.10 \qquad R^2 = 0.99 \tag{6}$$

L_1, R_1 and H_1 (cm) are the upward and downward movement distances, respectively, and R_1 (cm) is the horizontal diffusion radius of the wetting front under 0.01 MPa pressure. l_1 and h_1 (cm) are the upward and downward movement distances, respectively, and r_1 (cm) is the horizontal diffusion radius of the wetting front under 0.02 MPa pressure. R^2 is a multiple correlation coefficient. The analysis method used was introduced by Wang et al. [5].

式中L_1，R_1及H_1分别为压力 0.01MPa 情况下向上，向下垂直湿润峰运移距离，以及水平扩散半径，cm，l_1，h_1，r_1分别为压力 0.02MPa 情况下向上，向下垂直湿润峰运移距离，以及水平扩散半径，cm，R^2 为复相关系数，分析方法参见汪有科等[5]。

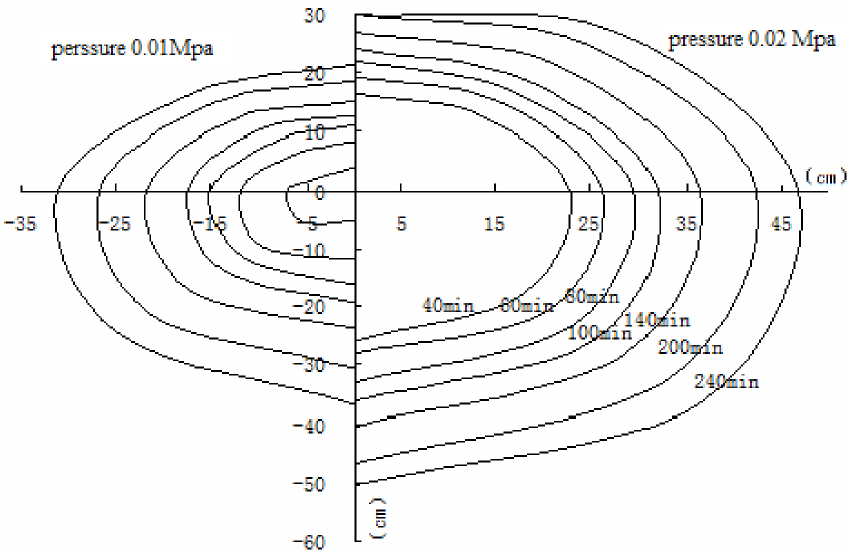

Fig. 4 - Movement curve of the wetting front under different pressure values

Effect of pressure on soil water movement and wetting front when using Ø25 mm irrigation pipelines with 2.5 mm pore diameter

Dynamic changes of the wetting front form in 4 h under infiltration irrigation using Ø25 mm irrigation pipelines with 2.5 mm pore diameter (pressure: 0.01 MPa and 0.005 MPa) were observed (Fig. 5). The graph on the left shows the wetting front under 0.01 MPa pressure,

在Φ25mm管、孔径为2.5mm组合的渗灌管下，压力对土壤水分运移和湿润体的影响

试验采用Ø25mm管孔径2.5mm渗灌管在两种压力在两种压力(0.01MPa, 0.005MPa)的情况下，在试验灌水过程对湿润体在沙土中形态变化进行了4小时动态观测，其变化见

and the one on the right is the wetting front under 0.005 MPa pressure. As irrigation continued, the wetting front of the soil increased gradually. However, it changed at different rates in the horizontal, upward, and downward directions. Under 0.01 MPa pressure, the horizontal and downward changes were obviously quicker than the upward change. After 4 h, the upward, horizontal, and downward infiltration diffusion lengths were 29.5, 37.6, and 36.5 cm, respectively. Under 0.005 MPa pressure, the wetting front changed more quickly in the downward direction than in the horizontal and upward ones. The upward, horizontal, and downward infiltration diffusion lengths 4 h later were 27.30, 36, and 36.3 cm, respectively. Infiltrations in different directions under 0.01 MPa and 0.005 MPa pressure agree with each other. The soil wetting fronts under two pressures were relatively even. The movement distance of the wetting front increased gradually with time, which shows a good correlation.

The fitting results are as follows:

Upward:

图5。由图5可看到,图的左半边为压力0.01MPa灌溉下湿润峰,右半边为压力0.005MPa灌溉下湿润峰,随着灌水时间的推移,土壤的湿润峰逐渐增加,但在水平,向上,向下各个方向上的湿润峰变化速度各不相同,在0.01MPa压力下,水平方向和垂直向下的方向要明显快于向上方向的湿润峰,4h后向上的入渗扩散距离为29.5cm,水平方向为37.6cm,垂直向下方向为36.5cm,在压力0.005MPa情况下土壤湿润峰向下的运移的速率高于水平方向和向上方向,4 h后向上的入渗扩散距离为27.30cm,水平方向为36cm,垂直向下方向为36.3 cm,压力0.01MPa情况下各方向上的入渗速度与压力0.005MPa情况下的基本一致,两个压力下土壤湿润峰都比较均匀。湿润峰运移距离随时间增加而逐渐变大, 两者具有较好的相关性, 拟合结果如下:

向上:

$$L_2 = 11.92Ln(t) - 30.26 \qquad R^2 = 0.978 \tag{7}$$

$$l_2 = 2.13Ln(t) - 24.47 \qquad R^2 = 0.979 \tag{8}$$

Downward:

向下:

$$H_2 = 13.22Ln(t) - 37.21 \qquad R^2 = 0.977 \tag{9}$$

$$h_2 = 8.17Ln(t) - 10.95 \qquad R^2 = 0.963 \tag{10}$$

Horizontal:

水平:

$$R_2 = 8.40Ln(t) - 19.05 \qquad R^2 = 0.99 \tag{11}$$

$$r_2 = 8.51Ln(t) - 11.84 \qquad R^2 = 0.96 \tag{12}$$

L_2, H_2, l_2, h_2, r_2, R^2 are the same as the aforementioned equations. The analysis method that was used was introduced by Wang et al. [5].

式中L_2, H_2, l_2, h_2, r_2, R^2同上,分析方法同汪有科等[5]。

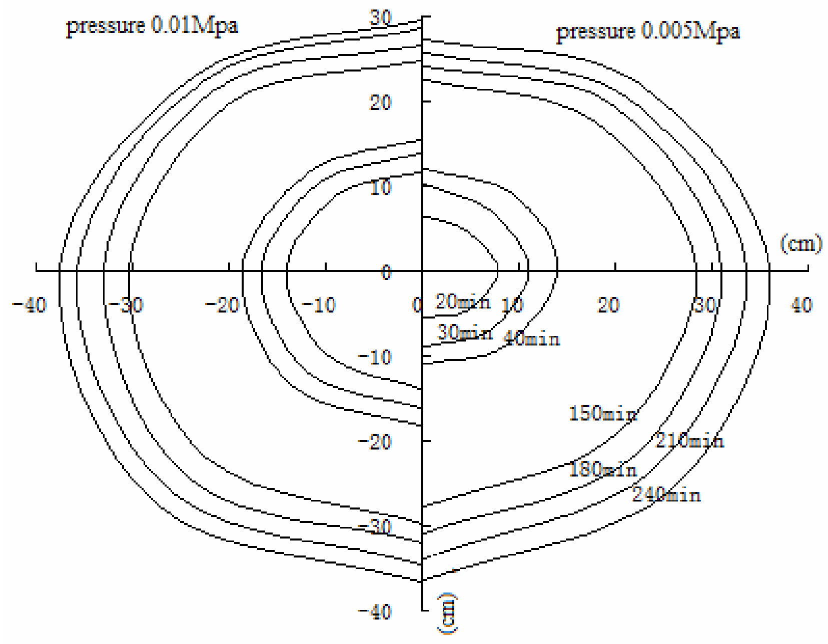

Fig. 5- Movement curve of the wetting front under different pressure values

Effect of different pipeline assembly on moisture movement and wetting front in sandy soil

Pipe size reflects the size of the contact surface between the water supply edges and soil [10]. In the laboratory simulation, given fixed pressure and bulk density, the morphological change of the wetting front is closely related with the infiltration pipe size and pore diameter. This experiment used two different pipeline assemblies (Ø25 mm irrigation pipelines with 2.5 mm pore diameter and Ø32 mm irrigation pipelines with 2 mm pore diameter), During the irrigation test, dynamic morphological changes of the wetting front in sandy soil in 5 h under 0.01 MPa pressure were studied (Fig. 6). The right graph shows the wetting front Ø25 mm irrigation pipelines with 2.5 mm pore diameter, whereas the left graph shows the wetting front Ø32mm irrigation pipelines with 2 mm pore diameter As irrigation continues, the wetting front increases gradually. However, it changes at different rates in the horizontal, upward, and downward directions. Under Ø25 mm irrigation pipeline with 2.5 mm pore diameter, the horizontal and downward changes were obviously quicker than the upward change. The upward, horizontal, and downward infiltration diffusion lengths 5 h later were 30, 40.25, and 40.8 cm, respectively. For the Ø32 mm irrigation pipeline with 2 mm pore diameter, the downward diffusion rate was higher than the horizontal and upward ones. The upward, horizontal, and downward infiltration diffusion lengths 5 h later were 22.45, 33.08, and 39.65 cm, respectively. Therefore, Ø25 mm irrigation pipeline with 2.5 mm pore diameter present quicker upward (25%) and horizontal (17%) infiltration compared withØ32 mm irrigation pipeline with 2 mm pore diameter. However, the infiltration rates under two pore diameters are similar. Viewed from the entire shape of the wetting front, the wetting front of Ø25 mm irrigation pipeline with 2.5 mm pore diameter is more even, which indicates that pore diameter should be changed to irrigate jujube trees. The movement distance of the wetting front lengthens gradually with time, which indicates a good correlation. The fitting results are introduced as follows:

According to the test results in sandy soil, the fitting results of Ø32 mm irrigation pipeline with 2 mm pore diameter are the same in Equations (1), (3), and (5), whereas the fitting results of Ø 25mm irrigation pipeline with 2.5 mm pore diameter are the same in Equations (7), (9) and (11).

Furthermore, water infiltration into soil slows down as time passes, especially in the radial and longitudinal directions. This reaction is due to the fact that at the beginning of irrigation, soil moisture content at the water outlet of the infiltration pipe reaches the saturation state quickly, thereby developing a great water potential difference with the surrounding soil. Consequently, soil water is driven to soil with low water potential. A wetting front with high soil moisture content inside and low moisture content outside is developed. With continuous expansion of the wetting front, the soil moisture gradient decreases, and the soil water potential difference will be reduced accordingly. Therefore, the infiltration rate of the wetting front decreases with the reduction of soil water potential.

不同管径和孔径组合渗灌管对土壤水分运移和湿润体的影响

管径的大小反映了供水边界和土壤接触面的大小[10]。在室内模拟试验时, 在压力和容重不变时, 沙土湿润峰形态变化与渗管的管径和孔径大小密切相关。本试验采用两种组合方式(Φ25mm管2.5mm孔径和Φ32mm管2mm孔径)的渗灌管, 在压力为0.01MPa的情况下, 在试验灌水过程对湿润体在沙土中形态变化进行了5小时动态观测, 其变化见图6。由图6可看到, 图的右半边为Φ25mm管2.5mm孔径渗灌管的湿润峰, 左半边为Φ32mm管2mm孔径渗灌管湿润峰, 随着灌水时间的推移, 土壤的湿润峰逐渐增加, 但在水平, 向上, 向下各个方向上的湿润峰变化速度各不相同, 在Ø25mm管径2.5mm孔径渗灌管下, 水平方向和垂直向下的方向要明显快于向上方向的湿润峰, 5h后向上的入渗扩散距离为30cm, 水平方向为40.25cm, 垂直向下方向为40.8cm, Ø32mm管径2mm孔径渗灌管下的湿润峰向下的扩散速度高于水平方向和向上方向, 5h后向上的入渗扩散距离为22.45cm, 水平方向为33.08cm, 垂直向下方向为39.65cm, Ø25mm管径2.5mm孔径渗灌管情况下向上和水平方向入渗速度比Ø32mm管径2mm孔径渗灌管情况下的快, 分别增加了25%和17%, 但是两个孔径向下的入渗速度相近,从湿润峰的整体性状看, Ø25mm管径2.5mm孔径渗灌管下湿润峰更加均匀, 从这个特点来看在枣树生产实践中应该应用该孔径。润峰运移距离随时间增加而逐渐变大, 具有较好的相关性, 拟合结果如下:

在沙土中测定结果, Ø32mm管径2mm孔径拟合结果同公式(1), (3)和(5)Ø25mm管径2.5mm孔径拟合结果为(7), (9)和(11)。

由图6还可以看出, 随时间推进水分在土壤中入渗速率逐渐降低, 水分在土体径向和纵向各方向推进速度逐渐降低。这是因为在灌溉开始时, 渗管出水口处的土壤含水率快速的达到饱和状态, 与周围土壤形成较大的土水势差, 高水势土壤驱使土壤水向低水势土壤运移, 形成了内高外低含水率梯度降低的湿润体。随着湿润峰的不断扩大, 内外土壤含水量差减小, 导致土壤水势差降低。因此, 湿润峰入渗速率会随着土壤水势的减小而降低。

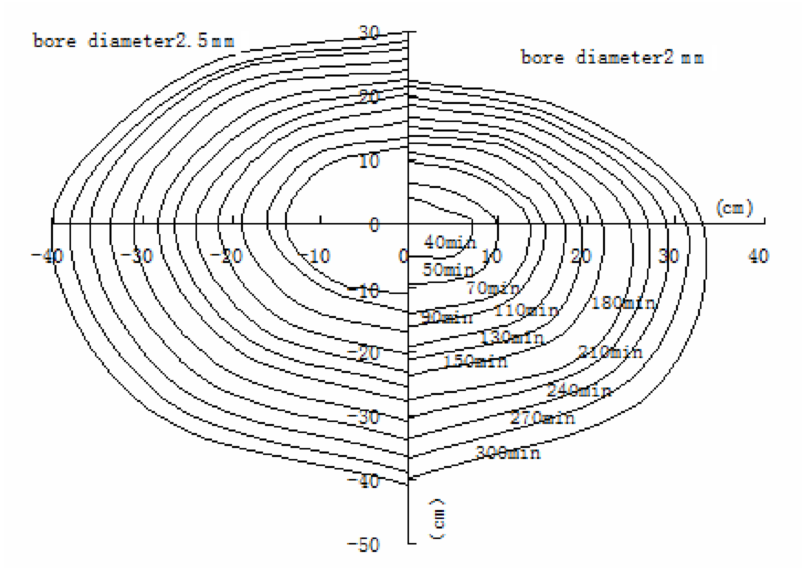

Fig. 6- Movement curve of the wetting front in sandy soil under different pore diameters

Effect of bulk density on moisture movement and the wetting front in sandy soil

Pore development in soil is closely related with the bulk density of soil and influences soil moisture transportation [7]. In the laboratory simulation, given fixed pressure and pore diameter, the bulk density of soil during irrigation is a key influencing factor for the morphology of the wetting front. In this experiment, dynamic morphological changes of the wetting front in sandy soil for 3 h under two bulk densities of soil (1.54 and 1.43 g·cm^{-3}) but fixed 0.02 MPa pressure, Ø25 mm irrigation pipeline with 2.5 mm pore diameter were studied (Fig .7). The graph on the right is the wetting front under 1.43 g·cm^{-3} bulk density, while the graph on the left is the wetting front under 1.54 g·cm^{-3}. As irrigation continued, the wetting front increased gradually. However, it changed at different rates in the horizontal, upward, and downward directions. Under 1.43 g·cm^{-3} bulk density, the horizontal and downward changes were obviously quicker than the upward change. The upward, horizontal, and downward infiltration diffusion lengths 3 h later were 28.8 cm, 43.2 cm, and 49.2 cm, respectively. Under 1.54 g·cm^{-3} bulk density, the downward movement was quicker than the horizontal and upward movements. The upward, horizontal, and downward infiltration diffusion lengths 3 h later were 29cm, 40.5cm, and 45 cm, respectively. Infiltrations in different directions under 1.43 g·cm^{-3} bulk density basically agree with those under 1.54 g·cm^{-3} bulk density, which represents the strong water diversion of sandy soil. The wetting front changed slightly as the bulk density of soil varied. The movement distance of the wetting front increased gradually with time, presenting a good correlation. Fitting results are shown as follows:

The fitting results under 1.54 g·cm^{-3} bulk density are the same in Equations (2), (4), and (6).

The fitting results under 1.43 g·cm^{-3} bulk density are Upward:

容重对渗灌水分运移和湿润体的影响

土壤的孔隙状况与土壤容重密切相关并影响土壤水分传输[7]。室内模拟过程中,在压力和孔径一定时,灌溉时的土壤容重大小是影响湿润峰形态的一个关键因子。本试验采用两种容重(1.54g·cm^{-3},1.43g·cm^{-3}),在压力0.02MPa,Ø25mm 管 2.5mm 孔径渗灌管情况下,在试验灌水过程对湿润体在沙土中形态变化进行了 3 小时动态观测,其变化见图 7。由图 7 可看到,图的左半边为容重 1.43g·cm^{-3} 下湿润峰,右半边为容重 1.54g·cm^{-3} 下湿润峰,随着灌水时间的推移,土壤的湿润峰逐渐增加,但在水平,向上,向下各个方向上的湿润峰变化速度各不相同,在容重 1.43g·cm^{-3} 下,水平方向和垂直向下的方向要明显快于向上方向的湿润峰,3 h 后向上的入渗扩散距离为 28.8cm,水平方向为 43.2cm,垂直向下方向为 49.2cm,在容重 1.54g·cm^{-3} 情况下湿润峰向下的运移的速率高于水平方向和向上方向,3 h 后向上的入渗扩散距离为 29cm,水平方向为 40.5cm,垂直向下方向为 45cm,容重 1.43g·cm^{-3} 情况下个方向上的入渗速度与容重 1.54g·cm^{-3} 情况下的基本一致,说明沙土导水能力比较强,不同容重条件下的湿润锋变化不大,但是湿润峰运移距离随时间增加而逐渐变大, 两者具有较好的相关性, 拟合结果如下:

在容重 1.54g·cm^{-3} 情况的下拟合结果同(2),(4)和(6)

在容重 1.43g·cm^{-3} 情况的下拟合结果:

向上:

$$L_3 = 6.798Ln(x) - 8.055 \qquad R^2 = 0.943 \tag{13}$$

Downward:

向下：

$$H_3 = 11.738Ln(x) - 15.619 \quad R^2 = 0.943 \tag{14}$$

Horizontal:

水平：

$$R_3 = 10.227Ln(x) - 11.575 \quad R^2 = 0.9867 \tag{15}$$

Where L_3, H_3, R_3 and R^2 are the same as the aforementioned equations. The analysis method that was used is that of Wang et al. [5].

式中L_3,H_3,R_3和R^2 同上,分析方法参见汪有科等[5]。

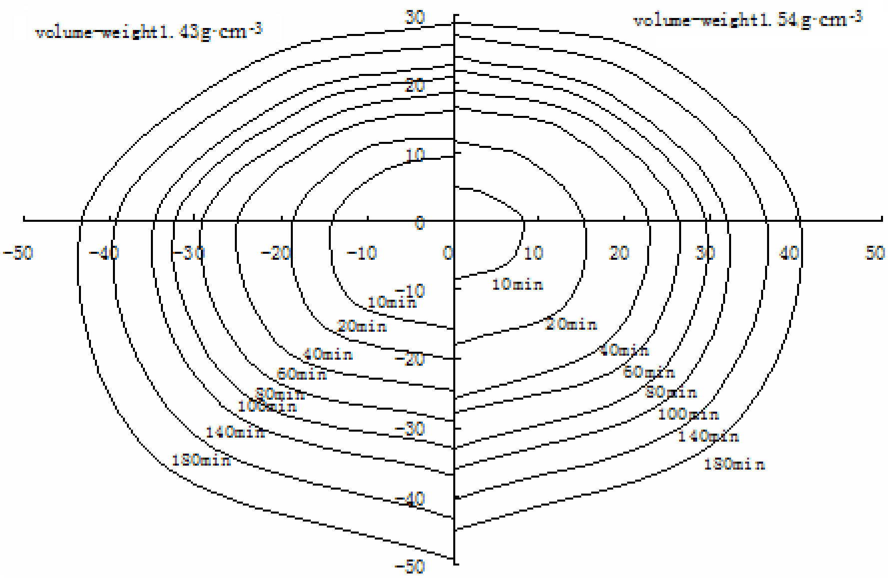

Fig. 7- The spool's rising rate in sand soil

CONCLUSIONS

Arid and semi-arid regions that suffer serious water shortage urgently need water-saving irrigation. Infiltrating irrigation is a new water-saving irrigation method that has attracted significant research attention because of its unique advantages [14,15]. Soil moisture infiltration under infiltrating irrigation is influenced by various factors [13,16]. This paper discussed only the effect of pressure, pore diameter, and bulk density on the wetting front of soil. The experiments obtained the following findings:

(1) Pressure is the key influencing factor for draining water from the infiltration pipe. The wetting front of sandy soil increases gradually under three hydraulic head pressures (0.02, 0.01, and 0.005 MPa) as irrigation continues. Horizontal and downward infiltrations are quicker than upward infiltration. For Ø32 mm irrigation pipeline with 2 mm pore diameter, the wetting front diffuses significantly more quickly under 0.02 MPa head pressure coMPared with 0.01 MPa head pressure. For the Ø25 mm irrigation pipeline with 2.5 mm pore diameter, the wetting fronts under 0.01 MPa and 0.005 MPa m pressure are similar.

(2) Infiltration pipe size and pore diameter affect soil moisture movement. The wetting front of sandy soil increases gradually with time under two pipeline assembly (Ø25 mm irrigation pipelines with 2.5 mm pore diameter and Ø32 mm irrigation pipelines with 2 mm pore diameter). It similarly varies under different pore diameters. The upward and horizontal infiltration rates

结论

在干旱半干旱地区水资源短缺,节水灌溉刻不容缓,渗灌作为一种新的节水灌溉方式,其特有的优点吸引众多学者对此进行研究[14,15],影响渗灌土壤水分入渗过程受多因素影响[13,16],本文只探讨了压力,孔径和容重对等对土壤湿润体的影响,其结果表明：

(1) 压力是影响渗灌管出水的关键因子。三种水头压力下(0.02,0.01,0.005 MPa),随着灌水时间的推移,沙土的湿润峰均逐渐增加,在水平和向下的入渗运移速率高于向上方向,在 Ø32mm 管径 2mm 孔径渗灌管,水头压力 0.02MPa 情况下在各个方向上湿润峰扩散的速度显著高于 0.01MPa 水头压力,在 Ø25 管径 2.5mm 孔径渗灌管,水头压力 0.01MPa 情况下各方向上湿润峰与 0.005MPa 水头压力变化差异不大。

(2) 渗管管径和孔径大小影响土壤的水分运动的过程。两种组合方式 (Φ25mm 管 2.5mm 孔径和 Φ32mm 管 2mm 孔径)渗灌管条件下,随着时间的推移,沙土湿润峰均逐渐增加。在不同孔径下湿润峰变化趋势基本一致。Ø25mm 管径 2.5mm 孔径渗灌管情况下向上和水平方向入渗速度比

under the Ø25 mm irrigation pipeline with 2.5 mm pore diameter are higher than those under theØ32 mm irrigation pipeline with 2 mm pore diameter. However, no significant difference of downward infiltration rate is detected. The wetting front under the Ø25 mm irrigation pipeline with 2.5mm pore diameter is more even.

(3) Bulk density of soil is the main influencing factor for water movement rate. Under 0.02 MPa pressure, Ø25 mm irrigation pipeline with 2.5 mm pore diameter, the wetting front of soil increases gradually under two bulk densities of soil as irrigation proceeds. The horizontal and downward infiltrations are quicker than the upward infiltration. However, the movement distance of the wetting front remains the same under two bulk densities of soil. This finding reflects that sandy soil has strong water diversion capability, and low bulk density is not the main restriction to soil moisture movement.

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Ø32mm 管径 2mm 孔径渗灌管情况下的快,向下方向两孔径无明显差异,从湿润峰的整体性状看,Ø25mm 管 2.5mm 孔径渗灌管下湿润锋的性状更加均匀。

(3) 容重是影响水分运移速率的一个主要因子。两种容重(1.54g·cm^{-3}, 1.43g·cm^{-3})下,在压力 0.02MPa,Ø25mm 管径 2.5mm 孔径渗灌管的情况下,随着灌水时间的推移,土壤的湿润峰逐渐增加,在水平和向下的入渗运移速率高于向上方向,但是两种容重(1.54g·cm^{-3}, 1.43g·cm^{-3},)情况下湿润峰相比较,各方向上的运移距离差异不明显,说明沙土的导水输水能力较强,而低容重不是限制水分运移的主因素。

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