1 材料与方法

1.1 室内试验装置

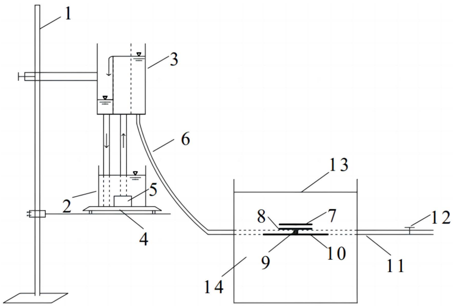
试验装置由自循环恒位水箱、供水箱、水泵、电子秤、输水软管、滴灌管、调控膜及试验土箱组成。通过调节水箱高度实现设计流量；输水装置为橡胶软管和 1 m 长的滴灌管（$\phi16$）；试验土箱基于亚克力板裁切组装而成，规格为 90 cm×45 cm×70 cm（长×宽×高），在距箱顶 35 cm 处设置直径 20 mm 的对称小孔，滴灌管从小孔穿过，滴头位于土箱长边中心，并在距离土箱顶边缘 35 cm 的下部打孔，方便取膜下部分土壤；调控装置为双层结构，上层为不透水聚乙烯薄膜和透水基质层过滤棉（长×宽=20 cm×10 cm），下层为不透水聚乙烯薄膜（长×宽=40 cm×20 cm），将调控膜的上层和下层结构分别放置在滴头上、下方，上膜和下膜的对称中心与滴头重合。试验装置见图 1。

1.2 室内试验目的

室内试验的目的是为 HYDRUS-2D 模型模拟试验提供物理参数，并利用所测得的试验结果对模型参数进行校验，以确保所建立的模型具有较高的精度，为后续的模型应用提供可靠基础。

1.3 现场试验设计

试验土壤取自雄安试验田，经过颗粒分析仪得到其粒径组成。将粒径组成和体积质量（表 1）输入到 HYDRUS-2D 内置的神经网络预测模型，即可得到土壤水力参数（表 2）。试验前将土壤风干并过 2 mm 筛，土壤按体积质量 1.38 g/cm^3 进行分层装土，进行层间打毛，将土壤均匀装入土箱内，采用带舌片的地下滴灌管灌水，管径为 16 mm。截取中间有一个滴头的 1 m 长管道，沿着土箱长边一侧布置，埋深 35 cm，所有处理均供水 9 h。供水结束后在膜上土壤进行垂直取样，膜下土壤从土箱侧边的开孔进行取样，采用烘干法测定土壤含水率。



注 1.支架；2.供水箱；3.恒位水箱；4.电子秤；5.水泵；6.输水软管；7.上膜（聚乙烯薄膜）；8.透水夹层（过滤棉）；9.滴头；10.下膜（聚乙烯薄膜）；11.滴灌管；12.止水夹；13.土壤表面；14.试验土箱。

图 1 试验装置示意

Fig.1 Schematic diagram of the testing device

表 1 土壤颗粒级配

Tab.1 Soil particle result table

颗粒占比	砂土/%	粉土/%	黏土/%	体积质量/(g cm^{-3})
砂质黏壤土	54.31	30.24	15.45	1.38

表 2 土壤水力参数

Tab.2 Soil hydraulic parameter table

相关参数	残留土壤含水率θr	饱和土壤含水率θs	土壤持水函数中的参数 α/cm^{-1}	土壤持水函数中的参数n	饱和导水率Ks/(cm h^{-1})	电导率函数中的弯度参数l
砂质黏壤土	0.05	0.39	0.02	1.48	1.31	0.5

2 HYDRUS-2D 模型的建立及验证

2.1 水分运移方程

采用 HYDRUS-2D[16-17]进行水分运移模拟，假定土壤为均质、各项同性的刚性多孔介质，不考虑温度和空气湿度对土壤水分运移的影响，采用二维 Richard 方程描述水分运动过程，方程中的土壤水分特征参数采用 VG 模型描述，详见文献[17]。

2.2 饱和区半径的确定

对于试验土壤，在假设饱和区半径为一定值 R（cm）和饱和区内积水厚度为 0.15 cm 的条件下，应用 HYDRUS-2D 模拟土壤水分运动（水量平衡误差为0.5%），土体增加水量与时间的比值为滴头流量 q（L/h），q和R之间的关系为：

$$R=5.60q^{0.8}, \tag{1}$$

2.3 初始与边界条件

依照试验土箱尺寸，建立膜调控润灌水运移模拟计算区域为一横向 45 cm、纵向 90 cm 的矩形区域。假设区域内初始土壤均匀分布于试验区域，则土壤水分的初始体积含水率为 26%。边界条件共包含 3 种，其中零通量边界模拟土箱外围亚克力板，变通量边界条件模拟滴头出水后在透水夹层边缘向土壤渗水口，大气边界模拟土箱顶上的开放状态。为分析模型中各点含水率变化和各处理之间的区别，在模型中设置了 17 个观测点（表 3），便于对含水率进行分析与和比较，观测点坐标见表 3。

2.4 模型验证

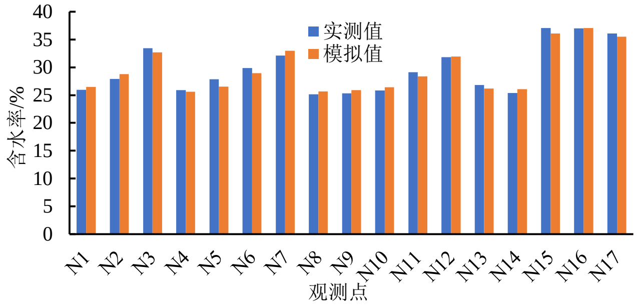
采用相对误差、决定系数（R^2）和均方根偏差（$RMSE$）评价 HYDRUS-2D 模型的模拟效果。R^2 越高、$RMSE$ 值越小，说明模拟效果越好。

图 2 为不同滴头流量下土壤含水率模拟值和实测值的柱状图。实测值与模拟值的相对误差<5%，HYDRUS-2D 模拟结果与实测值相差不大，因此 HYDRUS-2D 模型可以较为准确地模拟膜调控润灌条件下的水分运移。

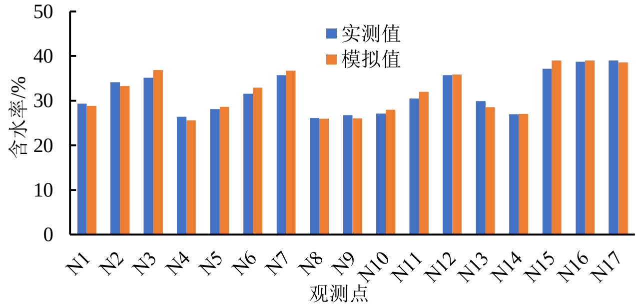
表 3　观测点坐标

Tab.3　Coordinates of observation points

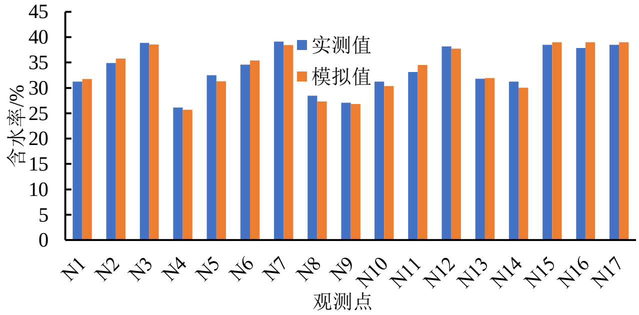
观测点编号	观测点坐标	观测点编号	观测点坐标	观测点编号	观测点坐标
N1	（5，17.5）	N7	（10，7.5）	N13	（15，-2.5）
N2	（5，12.5）	N8	（10，-2.5）	N14	（15，-7.5）
N3	（5，7.5）	N9	（10，-7.5）	N15	（5，2.5）
N4	（5，-2.5）	N10	（15，17.5）	N16	（10，2.5）
N5	（10，17.5）	N11	（15，12.5）	N17	（15，2.5）
N6	（10，12.5）	N12	（15，7.5）	-	-



(a) 0.9 L/h



(b) 2.1 L/h



(c) 3.2 L/h

图 2　不同流量下土壤含水率模拟值/实测值

Fig.2　Simulation value/measured value of soil moisture content under different flow rates

2.5　模拟试验的设计

膜调控润灌系统主要依靠土壤毛管吸力实现水分的向上运移。因此，土壤孔隙度是影响膜调控润灌灌溉性能的一个关键参数，土壤孔隙度是指土壤中的孔隙体积占总体积的比例。土壤孔隙度主要受到土壤类型的影响。灌溉水流量也会影响灌溉效果，模拟试验的因素为土壤类型和滴头流量，土壤类型分为砂土、壤土、砂质黏壤土和粉土，滴头流量分为：0.9、2.0、3.2 L/h（表 4）。土壤水力参数见表 5。

表 4　模拟试验方案

Tab.4　Simulation value/measured value of soil moisture content under different flow rates

处理	土壤类型	滴头流量/(L h^{-1})
T1	砂土	0.9
T2	砂土	2.1
T3	砂土	3.2
T4	壤土	0.9
T5	壤土	2.1
T6	壤土	3.2
T7	粉土	0.9
T8	粉土	2.1
T9	粉土	3.2
T10	砂质黏壤土	0.9
T11	砂质黏壤土	2.1
T12	砂质黏壤土	3.2

表 5　土壤水力参数

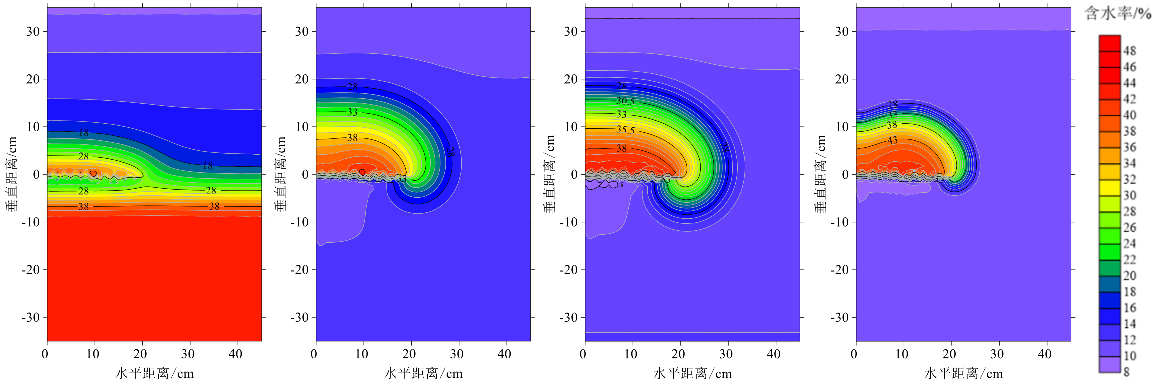
Tab.5　Soil hydraulic parameter table

土壤类型	残留土壤含水率 θr	饱和土壤含水率 θs	土壤持水函数中的参数 α/cm^{-1}	土壤持水函数中的参数 n	饱和导水率 Ks/(cm h^{-1})	电导率函数中的弯度参数 l
砂土	0.045	0.43	0.145	2.68	29.7	0.5
壤土	0.078	0.43	0.036	1.56	1.04	0.5
粉土	0.034	0.46	0.016	1.37	0.25	0.5
砂质黏壤土	0.050	0.39	0.020	1.48	1.31	0.5

3　结果与分析

3.1　膜调控润灌条件下不同土壤类型对水分运移的影响

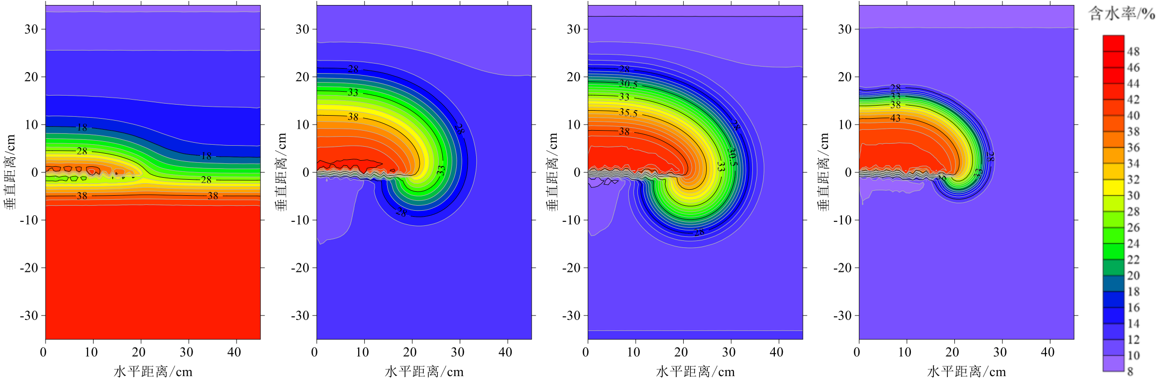
由图 3 可知，随着灌水时间的延长，除砂质土壤因导水率过大而造成水分大量渗漏外，其他 3 种土壤的湿润峰均向四周扩散，各处理在灌溉 24 h 后的湿润范围基本稳定，除砂土条件外，所有处理下的水分均向右的运移距离最大；灌水 24 h 后，除 T5、T12 处理外，其他处理下的水分向上运移距离均≥向下运移距离，T4、T7、T8、T9、T10 处理下的向上运移距离比向下运移距离大 5 cm，大大减少了灌



(a) 砂土　(b) 壤土　(c) 砂质黏壤土　(d) 粉土

图 5　2.1 L/h 灌水结束时含水率等值线图

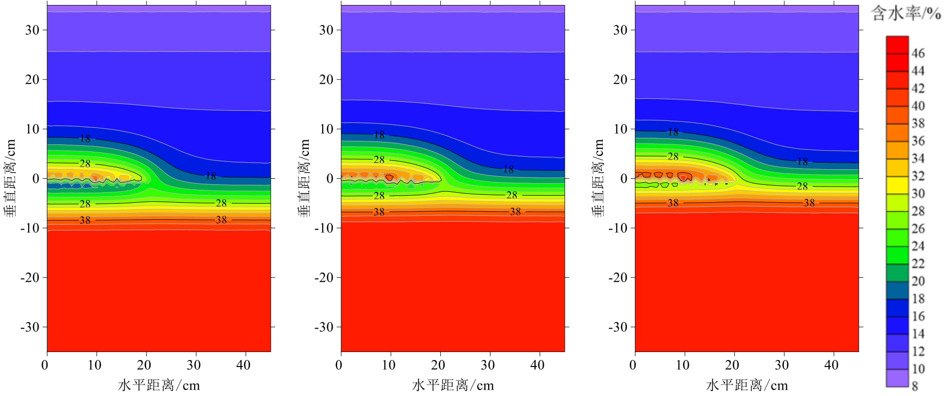
Fig.5　Contour map of moisture content at the end of 2.1 L/h irrigation



(a) 砂土　(b) 壤土　(c) 砂质黏壤土　(d) 粉土

图 6　3.2 L/h 灌水结束时含水率等值线图

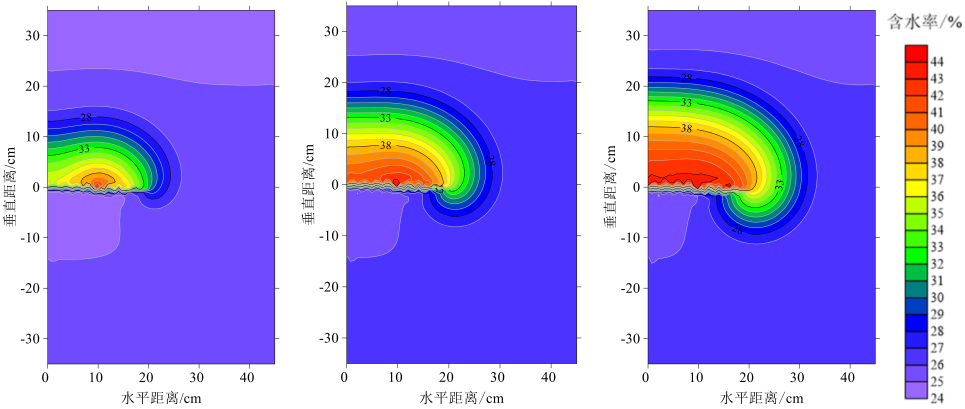
Fig.6　Contour map of moisture content at the end of 3.2 L/h irrigation



(a) 0.9 L/h　(b) 2.1 L/h　(c) 3.2 L/h

图 7　砂土灌水结束时含水率等值线图

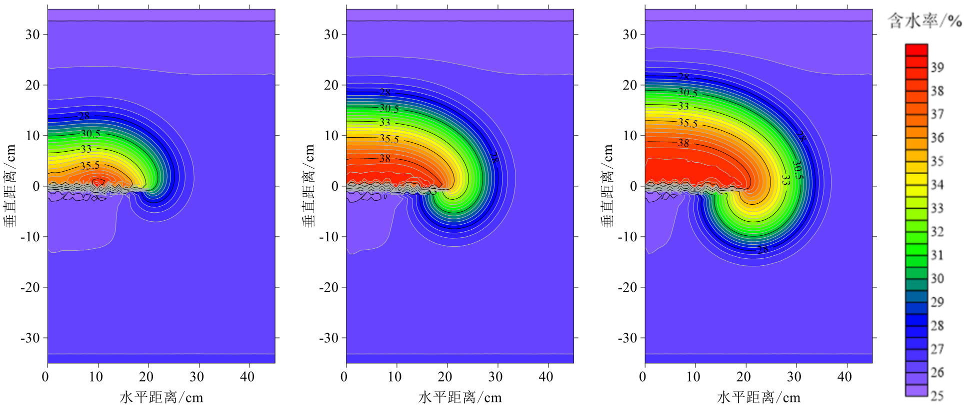
Fig.7　Contour map of moisture content at the end of sand irrigation



(a) 0.9 L/h　(b) 2.1 L/h　(c) 3.2 L/h

图 8　壤土灌水结束时含水率等值线图

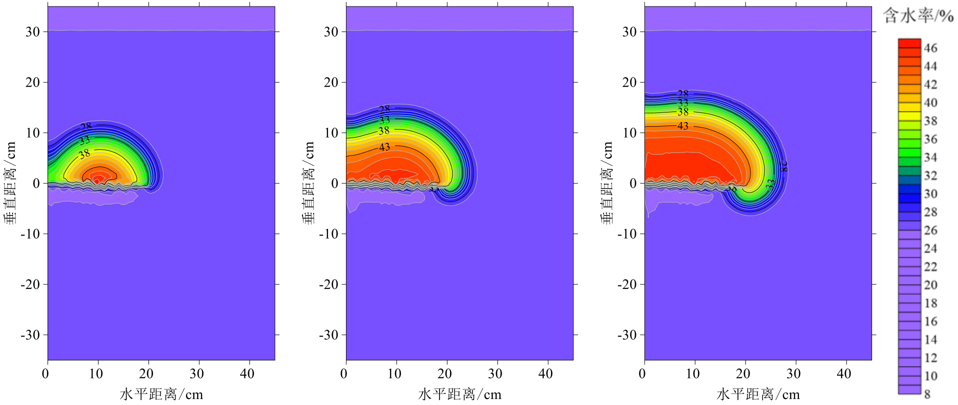
图 8　Contour map of moisture content at the end of loam irrigation



(a) 0.9 L/h (b) 2.1 L/h (c) 3.2 L/h

图 9 砂质黏壤土灌水结束时含水率等值线图

Fig.9 Contour map of water content at the end of irrigation of sandy clay loam

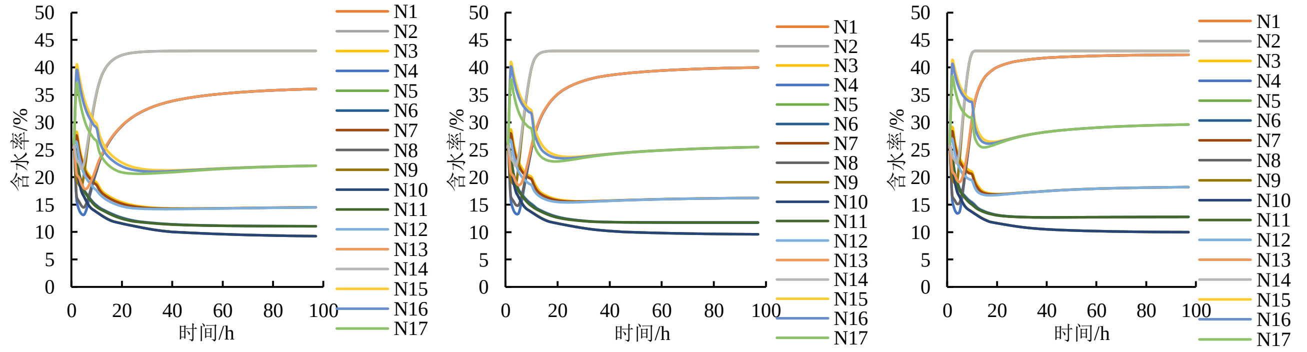


(a) 0.9 L/h (b) 2.1 L/h (c) 3.2 L/h

图 10 粉土灌水结束时含水率等值线图

Fig.10 Contour map of moisture content at the end of silt irrigation

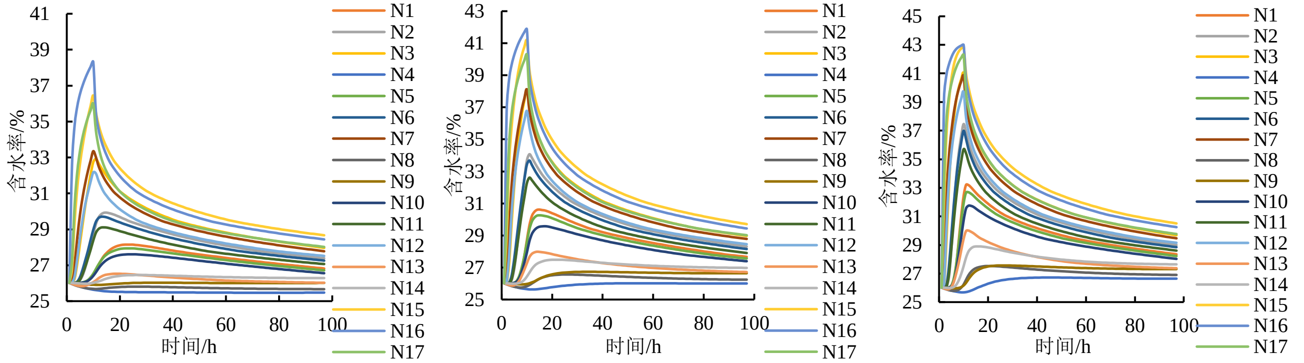
由图 11 可知，砂土条件下，除土箱底部的观测点外，其他观测点均在灌溉时有明显的土壤含水率下降过程，表明砂土条件下更容易造成渗漏。由图 12 可知，0.9 L/h 流量条件下，灌溉结束时观测点流量呈明显分层现象，N15、N16、N17（膜上 2.5 cm 处）的土壤含水率最高达 37%，N3、N7、N12（膜上 7.5 cm 处）的土壤含水率最高达 32%，N2、N6、N11（膜上 12.5 cm 处）的土壤含水率最高达 29.5%，说明膜调控润灌条件下灌水量的水平分布较为均匀，垂直方向上越靠近膜的位置含水率越高，随着滴头流量的增加，含水率分层现象逐渐消失。3.2 L/h 流量条件下，除膜下观测点外，膜上观测点的含水率都在灌溉结束时超过 30%，且没有明显分层现象，整体呈离膜越远含水率越小的趋势。砂质黏壤土条件下的观测点含水率总体与壤土类似（图 13）。粉土条件下，3 种流量均表现出了明显的分层现象，且随着滴头流量的增大，含水率高的观测点明显增加，故粉土更适宜用大滴头流量灌溉，可以达到更大的灌溉范围（图 14）。



(a) 0.9 L/h (b) 2.1 L/h (c) 3.2 L/h

图 11 砂土观测点含水率随时间的变化图

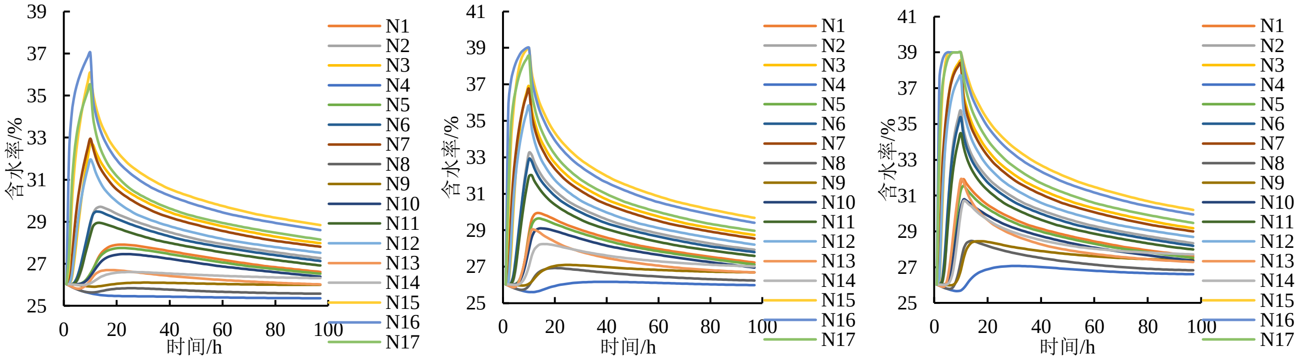
Fig.11 Change chart of moisture content of sand observation point with time



(a) 0.9 L/h　(b) 2.1 L/h　(c) 3.2 L/h

图 12　壤土观测点含水率随时间的变化图

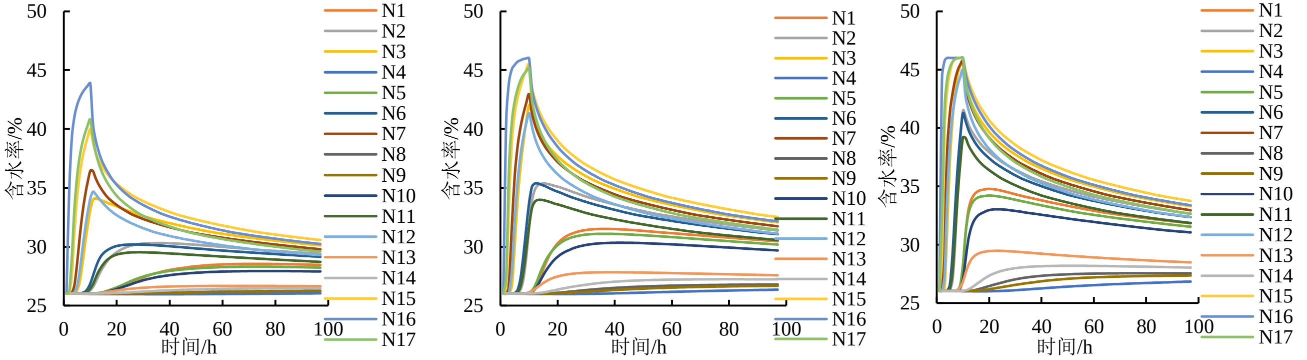
Fig.12 Change chart of moisture content of loam observation point with time



(a) 0.9 L/h　(b) 2.1 L/h　(c) 3.2 L/h

图 13　砂质黏壤土观测点含水率随时间的变化图

Fig.13 Change chart of moisture content of sandy clay loam observation point with time



(a) 0.9 L/h　(b) 2.1 L/h　(c) 3.2 L/h

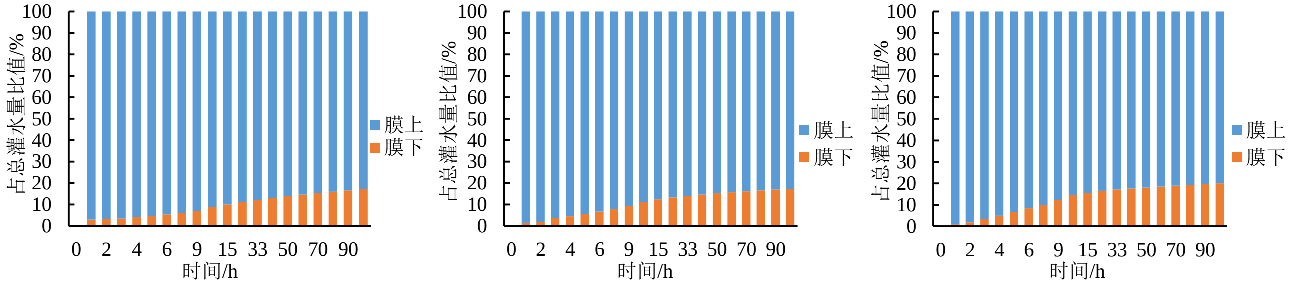
图 14　粉土观测点含水率随时间的变化图

Fig.14 Moisture content change chart of silt observation point with time

3.3　膜调控润灌条件下不同土壤类型和滴头流量对土壤水分分布的影响

将试验区域划分为膜上区域和膜下区域。在壤土、砂质黏壤土和粉土条件下（图 15—图 17），膜上水量占总灌水量的比值均可达到 70%以上，其中粉土可达到 90%以上。

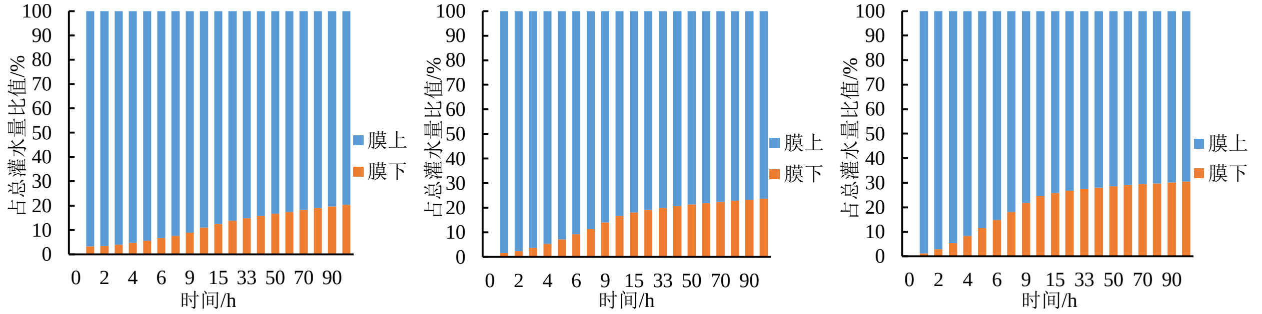
随着滴头流量的增加，壤土（图 15）和砂质黏壤土（图 16）膜下水量占总灌水量的比值逐渐增大。粉土条件下（图 17），虽然膜上水量占比随着滴头流量的增大而减小，但仍保持 90%以上的占比，可以适当加大滴头流量来增加湿润范围。



(a) 0.9 L/h　(b) 2.1 L/h　(c) 3.2 L/h

图 15　壤土膜上膜下水量占比图

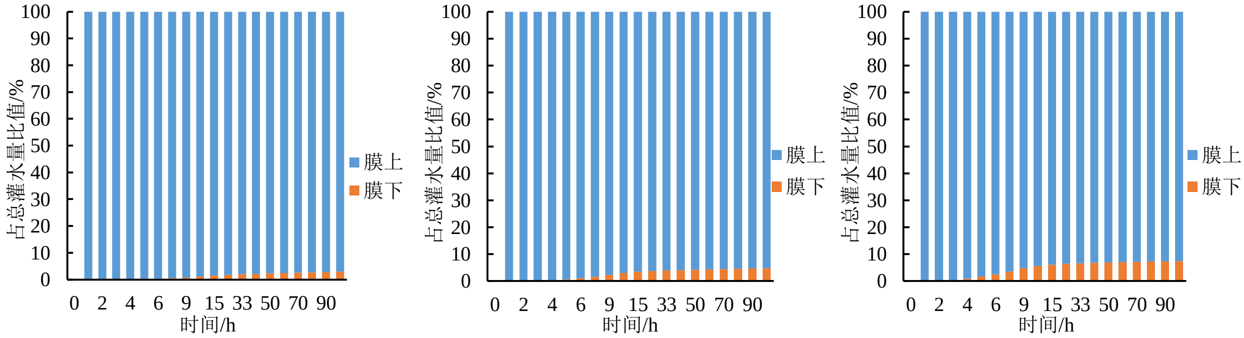
Fig.15 Proportion diagram of water volume on and under loam film



(a) 0.9 L/h (b) 2.1 L/h (c) 3.2 L/h

图 16 砂质黏壤土膜上膜下水量占比图

Fig.16 Proportion of water in sandy clay loam on and under the film



(a) 0.9 L/h (b) 2.1 L/h (c) 3.2 L/h

图 17 粉土膜上膜下水量占比图

Fig.17 Proportion diagram of water volume on and under silt film

随着灌水时间的延长，各处理膜上水量占比逐渐减小，直到灌水结束 24 h 后渐渐趋于平缓，此时各处理膜上水量占比远大于膜下水量占比。综上，膜调控润灌大大减少了灌溉水的深层渗漏，壤土和砂质黏壤土推荐采用 2 L/h 左右的滴头流量进行灌溉，粉土推荐采用 3 L/h 的滴头流量进行灌溉。

4 讨论

本研究分析了膜调控润灌条件下不同土壤类型和滴头流量下的土壤水分运移和分布规律。在运移距离、运移范围和膜上下水量占比等方面，不同土壤类型和滴头流量下的情况差异显著。从湿润峰运移距离来看，除砂土外，另外 3 种土壤湿润峰运移范围均随着时间的增大而增大，且运移速度由快到慢。这与白丹等[5]试验结果一致。相较于传统地下滴灌[18]，膜调控润灌大大增加了水分向上和水平方向的运移范围。从湿润范围方面来看，除砂土因渗漏量较大外，其他土壤类型均呈左右宽、上下小的椭球体湿润范围，这与其他地下滴灌方式[19-21]相比差异显著。例如，覆膜滴灌[10]、竖管滴灌[5,7-8]、微孔灌[22]条件下的湿润体均呈上下长、左右窄的纺锤体。这种现象表明，膜调控润灌可以增加灌水量在水平方向上的分布，减少深层渗漏，更有利于将水分保持在作物根区附近。在膜上、膜下水量占比方面，壤土、砂质黏壤土、粉土的膜上水量占比均可达到 70%以上，其中粉土则达到 90%以上，大大增加了根区含水率。随着滴头流量的增加，膜上水量占比有所下降，这与安巧霞等[23]研究结果相似。根据本试验结果，膜调控润灌技术在拓展湿润峰运移距离和增加根区含水率方面具有显著优势，在面对不同土壤类型和滴头流量时都有较好的适应性。

5 结论

1）HYDRUS-2D 模型可以较为准确地模拟膜调控润灌条件下不同土壤类型和滴头流量的水分运移过程。

2）在砂土中，膜调控润灌需要改变毛管埋深或膜的大小来进行灌溉，从而避免灌溉水深层渗漏。

3）砂质黏壤土和壤土条件下，推荐采用 2 L/h 左右的流量进行灌溉。在粉质土壤中，可采用较大的滴头流量进行灌溉。

（作者声明本文无实际或潜在利益冲突）

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Determining the technical parameters of the membrane-regulated subsurface irrigation for different soil types

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Abstract:【Objective】Membrane-regulated subsurface irrigation is a water-saving irrigation technique for water-scarce areas, and this paper is to experimentally determine its technical parameters for irrigation in soils with different textures.【Method】The studies were based on laboratory experiment and the HYDRUS-2D model. Infiltration of irrigation water into sandy soil, loam soil, sandy clay loam and silt soil under membrane -regulated irrigation was conducted experimentally with the dripping rate ranging from 0.9 to 3.2 L/h. The measured data were used to calibrate the HDYDRUS-2D model.【Result】The HDYDRUS-2D model can accurately simulate water flow in all soils under membrane regulated irrigation, with the relative errors less than 5%, the coefficient of determination and root mean square deviation being 0.97 and 0.007, respectively. The sandy soil was prone to leakage due to its elaborated hydraulic conductivity. In the membrane-regulated irrigation, adjusting the flow rate in the drip irrigation pipe was needed to improve irrigation efficiency in different soils. On average, the membrane-regulated irrigation worked well for all three soil types. At the end of the irrigation, the ratio of the water on the membrane to the total irrigation amount was more than 70% in all soils, indicating a reduction in water leakage loss. As the dripping rate increased, the proportion of water on the film in the loam soil decreased gradually; the dripping rate in irrigation for this soil should be controlled below a critical value. In the sandy soil, it was required to adjust the buried depth of the drip irrigation pipes to reduce leakage loss. The optimal dripping rate for the sandy clay loam soil and the loam soil was 2 L/h. As the flow rate increased, there was no significant change in the proportion of water on the membrane in the silt soil; the optimal dripping rate for the silt soil was 3 L/h.【Conclusion】Our experimental and numerical studies showed the optimal dripping rate for the membrane - regulated surface drip irrigation was 2 L/h for the sandy clay loam soil and the loam soil, and 3 L/h for the silt soil.

Key words: soil types; membrane-regulated irrigation; water transport; HYDRUS-2D model

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Effects of livestock wastewater irrigation on growth, yield, and water and nitrogen use efficiency of garlic

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Abstract:【Objective】Garlic is a cash crop in Dali, but its irrigation with livestock wastewater risks environmental pollution. This paper studies the combined effect of livestock wastewater irrigation and nitrogen fertilization on growth, yield, water and nitrogen utilization efficiency of garlic, as well as soil nitrogen in attempts to screen a sustainable livestock wastewater irrigation schedule for garlic production in this region.【Method】The experiment was conducted at the National Agricultural Environmental Dali Observation and Experimental Station. There were five treatments: freshwater irrigation without nitrogen application (CK), freshwater irrigation with 390 kg/hm^2 of nitrogen application (C1), freshwater irrigation with 312 kg/hm^2 of nitrogen application (C2), livestock wastewater irrigation without nitrogen application (R1), livestock wastewater irrigation with 150 kg/hm^2 of nitrogen application (R2). In each treatment, we measured the growth indexes, including dry weight, height, stem diameter and leaf area index of the garlic at different growing stages, as well as yield, and water and nitrogen use efficiency of the garlic and soil nitrogen content.【Result】The growth of the garlic was the best in R2, but was comparable with that in R1 and C1; R2 gave the highest yield. Compared to CK, C1, C2, R1 and R2 increased the bulb yield by 111.30%, 81.23%, 98.19%, and 142.01%, respectively. The nitrogen absorption and use efficiency of R1 and R2 was 154.71% and 92.25% higher than that of C1, respectively; the nitrogen partial factor productivity of R1 and R2 was 110.75% and 47.63% higher than that of C1, respectively. Compared to C1, R1 reduced the irrigation water productivity and soil nitrogen in the 0-40 cm of soil layer by 29.19%, while R2 increased the irrigation water productivity by 2.34% and reduced soil nitrogen in the 0-40 cm of soil by 3.89%, respectively. Compared to C1, R1 and R2 increased nitrogen in the 0-20 cm of soil layer by 170.90% and 255.93% respectively.【Conclusion】Livestock wastewater irrigation combined with appropriate base nitrogen fertilization can sustain garlic growth and yield. Livestock wastewater irrigation improved the nitrogen use efficiency and nitrogen partial factor productivity, with limited effect on average soil total nitrogen.

Key words: livestock wastewater; irrigation; garlic; production; water and nitrogen use efficiency

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