

EFFECT OF PERMEABLE BOUNDARY OF WATER-CONDUCTING DEVICE ON WATER AND SALT TRANSPORT UNDER INDIRECT SUBSURFACE DRIP IRRIGATION

导水装置透水边界对间接地下滴灌水盐运移的影响

Assoc. Prof. QiaoXia An¹⁾, Assoc. Prof. Ph.D. Stud. SanMin Sun^{*1,2)}, M.S. Rong Xu¹⁾,
Stud. JingHao Zhao¹⁾, Stud. KaiKai Gu¹⁾ Stud. Hong Cai¹⁾, Stud. JingYang Ma¹⁾,

¹⁾College of Water Conservancy and Architecture Engineering, Tarim University, Alar / China

²⁾College of Water Resources and Civil Engineering, China Agricultural University, Beijing/ China

Corresponding author : Sanmin Sun, Tel: +8609974680383; Email: ssmaq@126.com

ABSTRACT

Indirect subsurface drip irrigation is an effective means for water-conservation irrigation. The diameter of water-conducting device and height of permeable boundary are two important design parameters for such irrigation. In this study, there were analyzed the effects of water-conducting device diameter and permeable stratum height on the characteristics of wetting front and water-salt distribution through a laboratory test. Results demonstrated that the two parameters have influenced the size and shape of the wetting, and they effected on water and salt transport in the wetting front. The suitable diameter of water-conducting device, height of permeable layer would be chosen to regulate of tree root growth, and to reduce effects of soil salinity on tree.

摘要

间接地下滴灌是一种节水高效的灌溉方式，其导水装置直径、透水边界是灌溉设计的重要参数，本文通过室内试验，分析导水装置直径、透水层高度对湿润体特征及湿润体内水盐运移的影响。结果表明：导水装置直径、透水层高度影响湿润体的大小和形状，同时也影响湿润体内水盐运移。选择适宜的导水装置直径，透水层高度，以调节作物根系的生长，同时减少土壤盐分对作物的影响。

INTRODUCTION

Drought and soil salinization coexist in South Xinjiang, China (Wang et al, 2011; Hudan et al, 2012; Li et al, 2011). However, red jujube, a characteristic forestry fruit with high economic value, develops rapidly with sufficient sunshine and is widely planted in South Xinjiang. This forestry fruit has brought remarkable economic, ecological, and environmental benefits to the area (Hu et al 2016; Yao et al, 2011; Li et al, 2010). Nevertheless, a serious secondary soil salinization exists, which is caused by the outdated irrigation technology, low water utilization, and unreasonable irrigation. Drought and soil salinization restrict further development of forest and fruit industries. Therefore, determining water-conservation and salinity-control irrigations for local red jujube deserves research attention.

Indirect subsurface drip irrigation, a novel and highly efficient water-conservation irrigation technology, is composed of a common drip irrigation system on the earth's surface and a water-conducting device in soils underneath the drip irrigation emitter. This water-conducting device consists of an upper impermeable boundary, a lower permeable boundary, and a permeable bottom (Zhao et al, 2009). The impermeable boundary generally uses polyvinyl chloride (PVC) tubes. Coarse sands are filled in these PVC tubes at certain depth below the bottom, hence forming a cylinder sand column below the tube bottom. The sand column and bottom surfaces are employed as the lower permeable boundary and permeable bottom layers, respectively. Water penetrates into surrounding soils through the permeable boundary and bottom layers. Indirect subsurface drip irrigation transports water directly into deep soils, where crop roots grow in, but holds the wetting front within the underground, thus reducing the evaporation of unavailable water on the soil surface, determining high water utilization, and saving water (Meshkat et al, 2000). This kind of irrigation is applicable to characteristic jujube in South Xinjiang. To obtain the optimum technological parameters and improve water utilization, the variation law of wetting front under different technical conditions and water-salt distributions in the wetting front after irrigation should be explored. Therefore, the current work studied the law of soil water-salt motion in indirect subsurface drip irrigation through a laboratory test. The variation law of wetting front features and water-salt distribution in the wetting front under different diameters of the water-conducting device and different heights of the permeable stratum was analyzed to provide theoretical supports for the use of Indirect subsurface drip irrigation in jujube plantation in South Xinjiang.

MATERIAL AND METHOD

Water-conducting device components

The water-conducting components are shown in Fig. 1 (Sun *et al*, 2015; Sun *et al*, 2016), including the drip irrigation pipe, small pipe, adjusting valve, water-conducting device, coarse sand filling inside the water-conducting device, impermeable boundary (PVC pipe), permeable boundary (coarse sand), and permeable bottom (coarse sand).

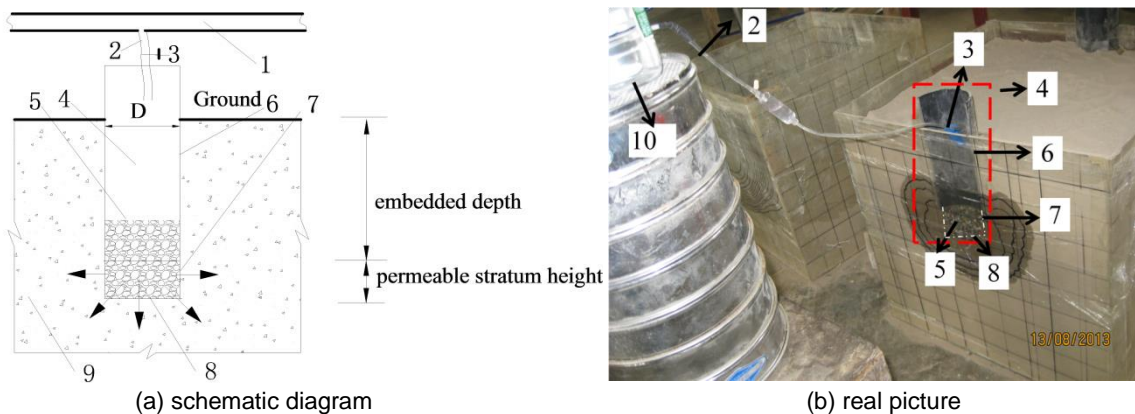


Fig.1 - Diagram of indirect subsurface drip irrigation components and irrigation principles

1-drip irrigation pipe (for the field); 2-small pipe; 3-regulating valve; 4-water-conducting device; 5-coarse sand; 6-impermeable boundary of the water-conducting device; 7- permeable boundary of the water-conducting device; 8-permeable bottom; 9-root zone soil; 10- The bottle for water (for laboratory test)

Method and materials

The laboratory test was implemented in the irrigation test site of the College of Water Resources and Architectural Engineering of Tarim University from June to August 2013. Sample soils were collected in the jujube block in the test site from soil layers containing the main roots (20–40 cm deep). Soil bulk density and initial salinity were 1.40 g/cm³ and 0.68 g/kg, respectively. Soil samples were air-dried and screened by a 1 mm sieve to eliminate impurities.

The test system is composed of an organic glass test soil box and a water service. The soil box is a 500 mm (L) × 500 mm (W) × 500 mm (H) cube made of 8 mm-thick organic glasses. The length, width, and height of the soil box were scaled at 50 mm units. The water service was self-made, which connected a 2.5 L water bottle with a medical infusion tube. This system can provide stable water flow.

The water apparatus used a piece of cylinder of PVC tube. This PVC tube was divided symmetrically at the diameter of the bottom circle, placed into certain depth at the 1/2 inside wall of the soil box, and finally installed into the testing soils. Gravels screened by a 2–5 mm sieve were filled into the bottom of the PVC tube. When the sample soils remained static for 24 h, the PVC tube was uplifted to a certain height, finally forming a semi-cylindrical permeable boundary.

Stopwatch was used in irrigation. During the first hour of irrigation, the location of the wetting front was marked by a piece of black marking pen on the soil box every 5 min; subsequently, it was marked every 10 min until the end of irrigation. The upward, downward, and horizontal moving distance of the wetting front was measured by a steel ruler, and each corresponding time was recorded.

After 24 h irrigation, soil samples were collected from different profiles at 10, 20, and 30 cm (Profiles A, B, and C) away from the water-conducting device horizontally. The sampling depth of each profile was 40 cm, and every 5 cm depth was determined as one soil layer. A total of 24 soil samples were collected. Soil moisture content was measured by oven-drying method. The electrical conductivity of leach liquor was measured with the DDSJ-308A conductivity meter (INESA) by mixing 5 and 25 g of dried soil and water, respectively.

Testing program: The test designed two diameters for the water-conducting device (50 and 90 cm) and three heights for the permeable stratum (0, 5, and 10 cm). Water flow and irrigation amount were fixed at 2 L/h and 4 L, respectively. Further details about the testing program are shown in Table 1.

Table 1

Testing program				
Test groups	Diameter of the water-conducting device	Height of the permeable stratum	Discharge	Irrigation amount
	[mm]	[mm]	[mm]	[L]
T1	50	0	2	4
T2	50	5	2	4
T3	50	10	2	4
T4	90	10	2	4

Data processing

The conversion between soil salinity content and soil conductivity is calculated as equation (1) (Zhang *et al*, 2011):

$$y = 3.63x + 0.108 \quad [\text{g/kg}] \quad (1)$$

where: x - the 1:5 soil water extract conductivity [ms/cm]; y - soil salinity content .

Statistical method

Excel was used for the data processing and variance analyses.

RESULTS

Effect of water-conducting device diameter on soil wetting front

For convenient analysis of wetting front features, the wetting front at different time points was drawn by a piece of pen. The effect of permeable boundary size on the wetting front at different times is shown in Fig. 2. The wetting front under indirect subsurface drip irrigation is basically elliptical. The maximum horizontal wetting front mostly occurs at the bottom of the sand column, whereas the maximum vertical wetting front is located in the middle axle of the water-conducting device. Considering the maximum horizontal wetting front as the symmetry axis, the vertical upward and downward wetting fronts are basically equal. This conclusion agrees with the report of Zhao *et al* (2009). The above observations may be related to the characteristics of indirect subsurface drip irrigation. When irrigation water entered soil mass, some water parts will penetrate into soils and distribute evenly at different directions in homogeneous isotropic soils. Meanwhile, some parts will move downward because of gravity effect, and the remaining part will be pushed into soils by the water accumulated in the water-conducting device. Given that these two water parts cause mainly the same effect, the vertical downward wetting front and the downward wetting fronts are basically equal to each other.

Given the fixed height of the permeable stratum, the wetting front develops from a slim pattern to a flat shape with the diameter increase of the water-conducting device [see Figs. 2(c) and 2(d)].

Moreover, given the fixed diameter of the water-conducting device, the wetting front develops vertically but shrinks horizontally as the permeable stratum rises [see Figs. 2(a), 2(b), and 2(c)].

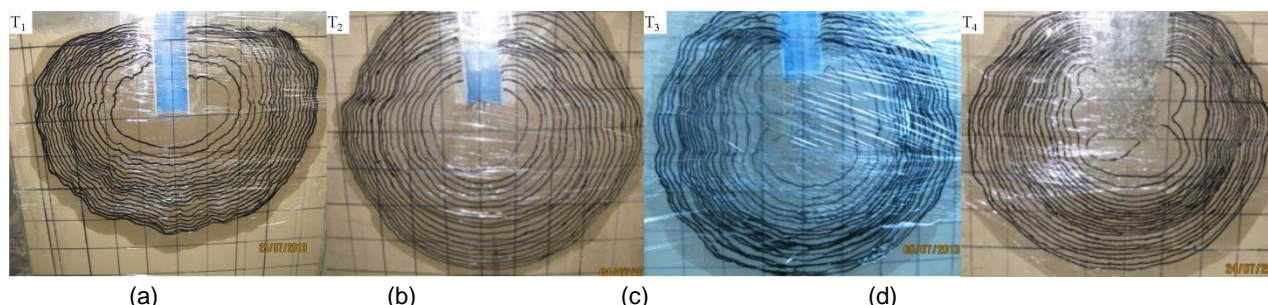


Fig.2 - Effect of permeable boundary size on wetting front (real shot)

Effect of permeable boundary of the water-conducting device on soil water distribution

In this experiment, the water-conducting device was buried 20 cm deep into the soil. After irrigation, the highest soil moisture content was detected in 20–30 cm soil layers near the outlet. Soil moisture content decreased gradually as the layer moved farther from the outlet both vertically and horizontally (see Fig. 2).

Under the same conditions, with the diameter increase of the water-conducting device, the soil moisture content of Profiles A and B near the outlet decreases, whereas that of Profile C increases. Therefore, the increase in diameter of the water-conducting device can expand the wetting front horizontally and increase its volume, thus reducing the soil moisture content in the wetting front, which is in accordance with previous research (Li et al, 2010).

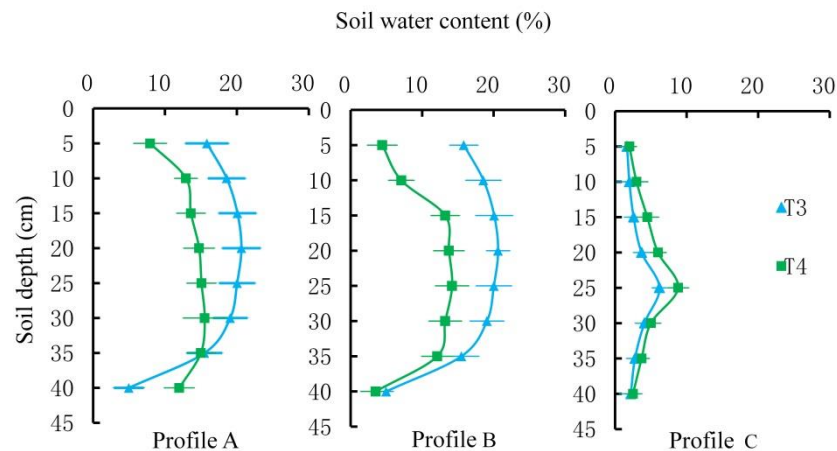


Fig.3 - Effect of water-conducting device diameter on soil water distribution

On Profiles A and B, T_1 is present significantly lower soil moisture content (30–40 cm) than the other test groups but higher soil moisture content (15–30 cm) on Profile C (see Fig. 4). The soil moisture content of T_3 on Profiles A and B changes more slightly than the other test groups, but that of T_3 on Profile C is higher than the other test groups. Therefore, increasing the permeable stratum can increase the vertical transport of water, whereas decreasing this parameter can increase the horizontal transport.

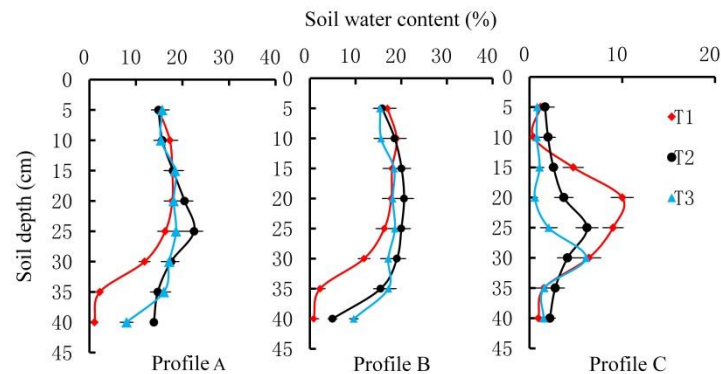


Fig.4 - Effect of permeable stratum height on soil water distribution

Effect of permeable boundary of the water-conducting device on soil salt distribution

When water entered the soil mass at the depth of 20–25 cm, the 20–30 cm-deep soil layers close to the outlet maintained high humidity, thus decreasing local soil salinity. As the water moves farther from the outlet vertically, water diffusion slows down gradually, and the leaching effect of water to soil salt weakens accordingly. This observation is manifested by the increasing soil salinity in upward and downward soil layers. As shown in Figs. 5 and 6, all the test groups showed decreased soil salinity at 20–30 cm depth but exhibited increased soil salinity at other vertical layers. Horizontally, the soil salinity of Profiles A and B is relatively lower, but that of Profile C is higher. The water-conducting device diameter and permeable stratum height can influence salt transport in the wetting front indirectly by affecting the wetting front size and water distribution. As shown in Fig. 5, when the diameter of the water-conducting device is small, the soil salinity of Profiles A and B is relatively lower, but that of Profile C is higher. This observation indicates that the small diameter of the water-conducting device can provide good leaching effect to soils near the outlet, but the leaching range is small. The larger diameter of the water-conducting device provides poorer salt-leaching effect near the outlet, but the leaching range expands.

Compared with other test groups, T_1 presents higher soil salinity at 30–40 cm soil layers on Profiles A and B but lower soil salinity at 20–30 cm soil layers on Profile C (Fig. 6). This result demonstrates that low

permeable stratum will reduce downward salt leaching but increase horizontal salt leaching. By contrast, high permeable stratum will increase downward salt leaching but reduce horizontal salt leaching.

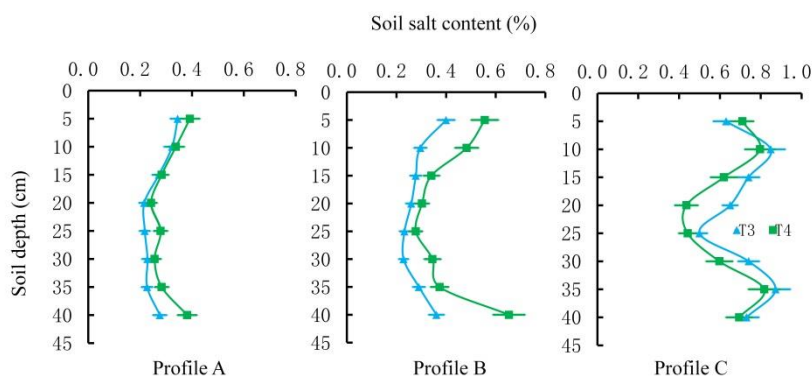


Fig.5 - Effect of water-conducting device diameter on soil salt distribution

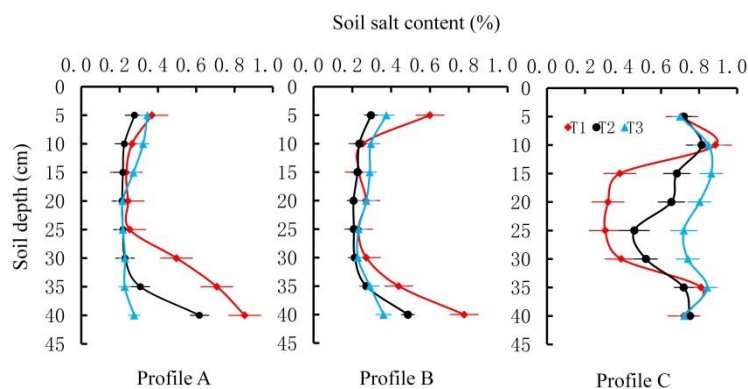


Fig.6 - Effect of permeable stratum height on soil salt distribution

CONCLUSIONS

(1) In indirect subsurface drip irrigation, the wetting front is basically elliptical. The maximum horizontal wetting front mainly occurs at the bottom of the sand column, whereas the maximum vertical wetting front is located in the middle axle of the water-conducting device. Considering the maximum horizontal wetting front as the symmetry axis, the vertical upward and downward wetting fronts are basically equal. Given the fixed height of the permeable stratum, the wetting front expands horizontally but narrows vertically with the increasing diameter of the water-conducting device. Moreover, given the fixed diameter of the water-conducting device, the wetting front develops vertically but shrinks horizontally as permeable stratum rises.

(2) After irrigation, the highest soil moisture content is detected in 20–30 cm soil layers near the outlet. Soil moisture content decreases gradually as the layer moves farther from the outlet both vertically and horizontally. With the increased diameter of the water-conducting device, the soil moisture content on Profile A and B close to the outlet decreases, whereas that on Profile C increases. Increasing the permeable stratum can increase the vertical water transport, whereas decreasing this parameter can increase the horizontal water transport.

(3) The lowest soil salinity is found in soil layers close to the outlet. Soil salinity increases gradually as the layer moves farther from the outlet. The small diameter of the water-conducting device can provide good leaching effect to soils near the outlet, but the leaching range is small. The larger diameter of the water-conducting device provides poorer salt-leaching effect near the outlet, but the leaching range expands. Furthermore, low permeable stratum will reduce downward salt leaching but increase horizontal salt leaching. By contrast, high permeable stratum will increase downward salt leaching but reduce horizontal salt leaching.

On the basis of the above results, high permeable stratum can induce downward growth of crop roots and relieve the influence of soil salinity on crop growth. Hence, this novel design should be used for the irrigation system of jujube tree. However, overly high permeable stratum will cause water penetration into deep soil layers and waste water resources. The diameter of the water-conducting device should be varied for the different growth stages of jujube tree: small diameter for young trees and large diameter for old trees. Nevertheless, this diameter design can produce an appropriate large wetting front for root to absorb water.

ACKNOWLEDGEMENT

This work was financially supported by the National Natural Science Foundation of China (Nos. 51069013 and 51369028), the College Students' Innovative Projects of China (No. 201410757004). The authors express their gratitude to Mr. HuanJie Cai, for his help in conducting this research.

REFERENCES

- [1] BaoLin Yao, SanMin Sun, Ma J, et al., (2011), Influence of irrigation quota on distribution of soil water and salinity for the drip irrigation of red jujube, *China Rural Water and Hydropower*, Issue 4, pp.88-91, ISSN 1007-2284, Wuhan University, Wuhan/China;
- [2] Hudan·T, Wu Zh G, Su L T, (2012). Numerical simulation of soil water-salt movement on drip irrigation cotton under film, *Soils*, vol.44, Issue 4, pp.665-670, ISSN 0253-9829, Institute of Soil Science, Chinese Academy of Sciences, Nanjing/China;
- [3] JiaShuai Hu, ZhenHua Wang, XuRong Zheng, (2016), A study on effects of drip irrigation modes on perennial red jujube under the condition of changing flood irrigation into drip irrigation, *Water-Saving Irrigation*, Issue 6, pp.31-35, ISSN 1007-4929, Wuhan University, Wuhan/China;
- [4] JingYe Li, Qiang Yuan, Hui Jiang, (2010), A discussion on development of featured forestry and fruit growing based on the regional adaptability, *Xinjiang Agricultural Sciences*, vol.47, Issue 4, pp.741-749, ISSN 1001-4330, Xinjiang Academy of Agricultural Sciences, Urumchi/China;
- [5] LiChun Wang, JianChu Shi, Qiang Zuo, et al., (2011), Establishing and validating the root water uptake model of winter wheat under salt stress conditions, *Transactions of the Chinese Society of Agricultural Engineering*, vol.27, Issue 1, pp.112-117, ISSN 1002-6819, Chinese Society of Agricultural Engineering, Beijing/China;
- [6] Tao Li, Jianfeng Zhang, Huijuan Cheng, et al., (2010), The wetting front distribution characteristic and the fitting model of single point free infiltration under deep pit irrigation in the field, *Agricultural Research in the Arid Areas*, vol.28, Issue 4, pp.36-39, ISSN 1000-7601, Northwest Sci-Tech University of Agriculture and Forestry, YangLin/China;
- [7] Meshkat M R C, Warner R C, Workman S R, (2000), Evaporation reduction potential in an undisturbed soil irrigated with surface drip and sand tube irrigation, *Transactions of the ASAE*, vol.43, Issue 1, pp. 79-86, ISSN 0001-2351, American Society of Agricultural and Biological Engineers / American;
- [8] SanMin Sun, QiaoXia An, HuanJie Cai. et al., (2015), Research on salt movement law in jujube root zone under indirect subsurface drip irrigation, *Transactions of the Chinese Society for Agricultural Machinery*, vol.45, Issue 1, pp. 160-169, ISSN 1000-1298, Chinese Society for Agricultural Machinery, Beijing/China;
- [9] Sun S. M., Yang P. L., An Q. X., et al., (2016), Investigation into surface and subsurface drip irrigation for jujube trees grown in saline soil under extremely arid climate, *European journal of horticultural science*, vol.81, Issue 3, pp. 165-174, ISSN1611-4426, International Society for Horticultural Science, Leuven/Belgium/China;
- [10] WeiXia Zhao, ZhenHua Zhang, HuanJie Cai, et al., (2009), Parameter model of water-conducting device specification for indirect subsurface drip irrigation, *Journal of Hydraulic Engineering*, vol.40, Issue 3, pp. 355-363, ISSN 0559-9350, Chinese Hydraulic Engineering Society, Beijing/China;
- [11] Yu, Zhang, LiHong, Wang, SanMin, Sun, et al., (2011), Indexes of salt tolerance of cotton in Akesu river irrigation district, *Scientia Agricultura Sinica*, vol.44, Issue 10, pp.2051-2059, ISSN 0578-1752, Chinese Academy of Agricultural Sciences, Beijing/China.