Effect of soil properties on Hydraulic characteristics under subsurface drip irrigation

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Abstract. Subsurface drip irrigation (SDI) is a technique that has a high potential in application because of its high efficiency in water-saving. The hydraulic characteristics of SDI sub-unit pipe network can be affected by soil physical properties as the emitters are buried in soils. The related research, however, is not fully explored. The laboratory tests were carried out in the present study to determine the effects of hydraulic factors including operating pressure, initial soil water content, and bulk density on flow rate and its sensitivity to each hydraulic factor for two types of SDI emitters (PLASSIM emitter and Heping emitter). For this purpose, three soils with contrasting textures (i.e., light sand, silt loam, and light clay) were repacked with two soil bulk density (1.25 and 1.40 g cm$^{-3}$) with two initial soil water content (12% and 18%) in plexiglass columns with 40 cm in diameter and 40 cm in height. Drip emitters were buried at depth of 20 cm to measure the flow rates under seven operating pressures (60, 100, 150, 200, 250, 300, and 370 kPa). We found that the operating pressure was the dominating factor of flow rate of the SDI emitter, and flow rate increased with the increase of operating pressure. The initial soil water content and bulk density also affected the flow rate, and their effects were the most notable in the light sand soil. The sensitivity of flow rate to each hydraulic factor was dependent on soil texture, and followed a descending order of light sand>silt loam>light clay for both types of emitters. Further, the sensitivity of flow rate to each hydraulic factor decreased with the increase of operating pressure, initial soil water content, and bulk density. This study may be used to guide the soil specific-design of SDI emitters for optimal water use and management.

1. Introduction

Subsurface drip irrigation (SDI) is a new and high efficient water saving technique extended from drip irrigation (DI). By using the SDI technique, water or mixture of water and nutrient can be applied slowly to the root zone through buried plastic tubes containing embedded emitters. Consequently, water and nutrients can be readily transported by capillary rise or gravity for uptake by root [1]. Compared with other irrigation techniques, the SDI has higher water saving efficiency because of its ability to decrease water loss introduced by leakage during the water transport, surface evaporation, and deep drainage. Meanwhile, The SDI can ensure timely allocation of suitable amount of water and nutrients to the root zone for crop requirement, which may improve crop quality and productivity [2]. Since the subsurface drip tubes do not occupy arable land as irrigation ditch requires, the land use efficiency can also be improved. The relatively dry soil in the surface during the SDI period can also
prevent the growth of weeds [3–4]. Therefore, it is significant to promote the application of SDI technique in agriculture. As a new saving irrigation technique, the SDI also has a lot of issues to be solved as the associated equipment development and technical research is not mature. Many studies have been done regarding the hydraulic characteristics of embedded emitters and factors affecting the flow rate of embedded emitters [5–7]. For example, Xu et al. (2003, 2004, 2016) explored the effects of emitter type, operating pressure on the flow rate using the orthogonal experimental design [8–11]. Warrick et al. (1996) and Shani et al. (1996) investigated the effects of soil hydraulic conductivity on flow rate of emitters [12–13]. In addition, many studies focused on soil effects on flow rate of emitters under point source infiltration condition by using experimental data and mathematical modeling [14–17]. However, all these above mentioned studies mainly focused on the effects of operating pressure and emitter type on flow rate of emitters, and few, if any, studies are available on the effects of soil physical properties on flow rate of emitters. Because the emitters of SDI are buried in soil, the hydraulic properties of embedded emitters are susceptible to the changes in soil physical properties which may also be complicated by their spatial variations. The objective of this study was to analyze the effects of operating pressure, initial soil water content, and bulk density on flow rate of two embedded emitters (i.e., PLASSIM emitter and Heping emitter). We expected that this study would provide robust theory for designing economic and high efficient water saving SDI system. Meanwhile, it is expected to provide reasonable parameters for SDI design and irrigation scheduling (e.g., irrigation amount and irrigation time).

2. Materials and methods

2.1. Soils

Three soils with contrasting soil textures were sampled at three fallow farmlands from Guanzhong Plain located at Shaanxi province in October 2014. A total of 60 squared areas each with approximately 2 m² were randomly selected. Soils were sampled from 10–30 cm after removing soils of top 10 cm. All air dried soils were sieved over a 2 mm screen. Initial soil water content (θ₀) was about 1% on weight basis. Soil particle size distribution was analyzed using the Malvern Mastersizer 2000 particle size analyzer produced in the UK. Soil particle fractions are shown in Table 1. The soil textures are light clay, silt loam, and light sand according to the Chinese soil texture classification system.

Table 1. Soil textures and soil particle fractions.

| Soil texture  | Soil particle fractions (%) | 0.05 ~ 1mm | 0.01 ~ 0.05mm | <0.001mm |
|--------------|----------------------------|------------|---------------|----------|
| Light clay   | 38.21                      | 28.70      | 32.02         |
| Silt loam    | 10.45                      | 61.13      | 0.90          |
| Light sand   | 55.75                      | 35.09      | 0.11          |

2.2. Experiment and data analysis

This study was conducted in plexiglass columns with 40 cm in diameter and 40 cm in height. Drip emitters were buried at a depth of 20 cm. Two types of emitters were used: one is PLASSIM emitter from Israel and the other is Heping emitter from Shaanxi Heping Technology Corporation. By taking the real application and experimental condition into consideration, seven operating pressures including 60, 100, 150, 200, 250, 300, and 370 kPa were used. Soils were repacked into the column with two bulk densities (1.25 and 1.40 g cm⁻³) and two initial soil water contents (12% and 18%) on weight basis. Uniform bulk density in the soil column was ensured by carefully repacked soils layer by layer. The drip emitter was first calibrated on the soil surface by determining the flow rate using the volumetric method. Results from the calibration indicated that the relationship between flow rate of drip emitter (q_DI) in L h⁻¹ and operating pressure (h) in kPa can be expressed as:
\[ q_{DI} = kh^x \]  

where \( k \) and \( x \) are empirical constants.

According to the experimental data, the relationship between \( q_{DI} \) and \( h \) for the PLASSIM emitter and Heping emitter can be characterized by:

\[ q_{DI,P} = 0.3610h^{0.5088} \]  
\[ q_{DI,h} = 0.1687h^{0.5390} \]  

where \( q_{DI,P} \) and \( q_{DI,h} \) represent the \( q_{DI} \) values for the PLASSIM emitter and Heping emitter, respectively. Flow rate of the SDI (\( q_{SDI} \)) in L h\(^{-1}\) can be calculated by:

\[ q_{SDI} = k\gamma^a\theta_0^c h^x \]  

where \( \gamma \) is bulk density in g cm\(^{-3}\); \( \theta_0 \) is the weight-based initial soil water content in %; \( k, a, c, \) and \( x \) are empirical constants.

### 3. Results and discussion

#### 3.1. Effects of hydraulic factors on the flow rate of drip emitters

**3.1.1. Effects of operating pressure on the flow rate of drip emitters**

Figure 1 shows the relationship between \( q_{DI} \) and \( h \) and also \( q_{SDI} \) and \( h \) for three soils. As it shows, the \( q_{DI} \) was significantly higher than \( q_{SDI} \) as we expected. For all three soils, the \( q_{SDI} \) increased with increase of \( h \). The effects of \( h \) on \( q_{SDI} \) became more similar among three soil textures as \( \gamma \) and \( \theta_0 \) increased. For example, when \( \gamma \) and \( \theta_0 \) at their lowest values of 1.25 g cm\(^{-3}\) and 12%, respectively, the \( q_{SDI} \) values under the same \( h \) were obviously different among soil textures. In this case, the \( q_{SDI} \) was the greatest for light sand and was the lowest for light clay. However, when \( \gamma \) and \( \theta_0 \) reached the highest values of 1.4 g cm\(^{-3}\) and 18%, respectively, the curves of \( q_{SDI} \) versus \( h \) for three soil textures overlapped. When \( \gamma, h, \) and \( \theta_0 \) were the same for three soil textures, the \( q_{SDI} \) values among three soils were comparable without significant differences:

**3.1.2. Effects of initial soil water content on flow rate of drip emitters**

Figure 2 shows the relationship between \( q_{SDI} \) and \( \theta_0 \). As Figure 2 shows, the \( \theta_0 \) had notable effects on \( q_{SDI} \), and the flow rate significantly decreased with the increase of \( \theta_0 \). This was because more porosity was filled with water at higher soil matrix potential. Under this condition, water nearby the emitter was easily stagnated around the emitter without unhindered water movement to the surrounding soils. Meanwhile, water flow in resistance to pressure was developed which further prevent water outflow from emitters and result in a reduced flow rate [18]. For a given \( \theta_0 \), \( q_{SDI} \) under different soil textures ranked in a descending order of light sand>silt loam>light clay (Figure 2). When bulk density was high (i.e., 1.4 g cm\(^{-3}\)), the \( q_{SDI} \) in the light sand decreased with the fastest rate as \( \theta_0 \) increased. This resulted in a lower flow rate of light sand compared to other two heavier soils at the \( \theta_0 \) of 18%. The pore size distribution of light sand was the most susceptible to the changes in bulk density. This, in turn, greatly affected the flow rate of the buried drip emitters (Figure 2a, 2b).
Figure 1. Flow rate of two types of drip emitters ((a) PLASSIM emitter and (b) Heping emitter) on the soil surface and subsurface of three soil textures versus operating pressure.

(a) PLASSIM emitter

(b) HEPING emitter

× surface soil  Δ sandy soil  Δ loamy soil  □ clay soil
Figure 2. Relationship between flow rate and initial soil water content for (a) PLASIMM emitter and (b) Heping emitter.

Δ sandy soil ◇ loamy soil □ clay soil
3.1.3. Effects of bulk density on flow rate of drip emitters Figure 3 shows the effects of $\gamma$ on $q_{SDI}$. As Figure 3 shows, the $q_{SDI}$ decreased linearly with the increase of $\gamma$ for a given $h$ and $\theta_0$. For a given $\gamma$, $q_{SDI}$ under different soil textures ranked in a descending order of light sand>silt loam>light clay, and the soil texture-associated differences in $q_{SDI}$ decreased with the increase of $\gamma$. This implies that effect of bulk density on flow rate of the emitter was more notable for coarser soils. The possible reason was associated with changes in soil porosity and pore size distribution which is highly related to the bulk density. In general, sandy soils have very developed macro-pores which favor good soil aeration and water permeability. Therefore, soil physical properties of sandy soils are more susceptible to the changes in bulk density than clayey soils [19].

In case of high $\gamma$ and $\theta_0$ (i.e., 18%), flow rate of the emitter in the light sand decreased at the highest rate with the increase of $\gamma$. As a consequence, the flow rate in the light sandy soil was even lower than other two heavier soils at the $\gamma$ of 1.4 g cm$^{-3}$. For a given $h$ and $\theta_0$, flow rate the emitter linearly decreased with the increase of bulk density. The soils become more dense and less water permeable at higher $\gamma$. In this case, the water nearby the emitters was easily stagnated around the emitter without unhindered water movement to the surrounding soils. Furthermore, water flow in resistance to pressure was developed which further prevent out flow from emitters and result in a reduced flow rate. On contrary, lower bulk density corresponds to higher water permeability. In this case, water outflow from the emitters suffered from less resistance, which resulted in relatively high flow rate.

3.2. Sensitivity analysis of flow rate to hydraulic factors

Sensitivity index can be used to characterize the sensitivity of flow rate to hydraulic factors. The greater value of sensitivity index indicates that the flow rate is more sensible to the change of a certain hydraulic factor. The partial derivative of the equation (4) with respect to each of three factors (i.e., $h$, $\theta$, $\gamma$), expressed as $\partial q_{SDI}/\partial h$, $\partial q_{SDI}/\partial \theta_0$, $\partial q_{SDI}/\partial \gamma$, respectively, was used to characterize the sensitivity of $q_{SDI}$ to hydraulic factors. The partial derivatives can be expressed as:

$$\frac{\partial q_{SDI}}{\partial h} = k\gamma^a\theta^b h^{x-1}$$  \hspace{1cm} (5)

$$\frac{\partial q_{SDI}}{\partial \theta_0} = k\gamma^a c\theta^{-1} h^x$$ \hspace{1cm} (6)

$$\frac{\partial q_{SDI}}{\partial \gamma} = k a\gamma^{x-1} \theta^c h^x$$ \hspace{1cm} (7)

Note that flow rate increased with $h$ but decreased with $\theta_0$ and $\gamma$, so the absolute value of $\partial q_{SDI}/\partial \theta_0$ and $\partial q_{SDI}/\partial \gamma$ were used to characterize the degree of sensitivity. Higher values of $\partial q_{SDI}/\partial h$, $|\partial q_{SDI}/\partial \theta_0|$, and $|\partial q_{SDI}/\partial \gamma|$ imply higher degree of sensitivity.

3.2.1. Sensitivity of flow rate to operating pressure Figure 4 shows the sensitivity index of $q_{SDI}$ versus $h$ for two types of emitters in three soils. Greater value of $\partial q_{SDI}/\partial h$ indicates more sensitivity of flow rate to the change in $h$. As Figure 4 shows, the $\partial q_{SDI}/\partial h$ values were relatively higher at lower $h$ values for both types of emitters, indicating that $q_{SDI}$ was more sensible to the change in $h$ at a lower operating pressure. The sensitivity decreased with the increase of $h$, demonstrating a reduced effect of operating pressure on flow rate. For a given $h$, the sensitivity of $q_{SDI}$ under different soil textures ranked in a descending order of light sand>silt loam>light clay for both types of emitters.
(a) $\theta_0 = 12\%, h = 100$ kPa

(b) $\theta_0 = 18\%, h = 100$ kPa

(c) $\theta_0 = 12\%, h = 350$ kPa

(d) $\theta_0 = 18\%, h = 350$ kPa

(a) PLASSIM emitter

(b) Heping emitter

Figure 3. Relationship between flow rate and bulk density for (a) PLASIMM emitter and (b) Heping

$\wedge$ sandy soil $\Diamond$ loamy soil $\Box$ clay soil
3.2.2. Sensitivity of flow rate to initial soil water content

Figure 4 shows the sensitivity index of $\frac{\partial q_{SDI}}{\partial h}$ versus $\theta_0$ for two types of emitters in three soils. Greater value of $|\frac{\partial q_{SDI}}{\partial \theta_0}|$ indicates more sensitivity of flow rate to the change in $\theta_0$. As Figure 5 shows, $|\frac{\partial q_{SDI}}{\partial \theta_0}|$ values were relatively higher at lower $\theta_0$ values for both types of emitters. The $\theta_0$ had strong effect on flow rate. The sensitivity of $q_{SDI}$ for both types of emitters decreased with the increase of $\theta_0$, demonstrating a reduced effect of $\theta_0$ on $q_{SDI}$ at wetter conditions. For a given $\theta_0$, the sensitivity of flow rate under different soil textures ranked in a descending order of light sand>silt loam>light clay for both types of emitters. This indicates that the flow rate in the light sand followed by the silt loam was the most susceptible to the change of initial soil water content.
3.2.3. Sensitivity of flow rate to bulk density  Figure 6 shows the sensitivity index of $\frac{\partial q_{SDI}}{\partial \gamma}$ versus $\gamma$ for two types of emitters in three soils. Greater value of $|\frac{\partial q_{SDI}}{\partial \gamma}|$ indicates more sensitivity of flow rate to the change in $\gamma$. As Figure 6 shows, $|\frac{\partial q_{SDI}}{\partial \gamma}|$ values was relatively stable with the change in $\gamma$. This implies that the sensitivity of flow rate was independent on bulk density although a slightly decreased $|\frac{\partial q_{SDI}}{\partial \gamma}|$ was observed with the increase of $\gamma$. For a given $\gamma$, the sensitivity of flow rate under different soil textures ranked in a descending order of light sand>silt loam>light clay for both types of emitters. This indicates that the flow rate in the light sand followed by the silt loam was the most susceptible to the change of bulk density.
4. Conclusions
Based on experimental research and data analysis, this study analyzed the effects of operating pressure, initial soil water content, and bulk density on flow rate of subsurface drip irrigation using two types of emitters (i.e., PLASSIM emitter and Heping emitter). The main conclusions are as follows:

(1) Operating pressure is the dominant factor of flow rate for all three tested soils. For a given operating pressure, flow rate in the subsurface of three soils was reduced to different extents as compared to that on soil surface. The lower bulk density and initial soil water content, the greater differences in the trend of flow rate as a function of operating pressure. The sensitivity of flow rate to operating pressure ranked in a descending order of light sand>silt loam>light clay for both types of emitters. The flow rate increased with the increase of operating pressure for all three soils. The sensitivity of flow rate to operating pressure decreased with the increase of operating pressure for both types of emitters.

(2) For a given operating pressure, both initial soil water content and bulk density affected the flow rate of both emitters, and their effects were more notable for coarser soils. For a given initial soil water content and bulk density, the sensitivity of flow rate to each of them ranked in a descending order of light sand>silt loam>light clay for both types of emitters. The sensitivity of flow rate to each of initial soil water content and bulk density decreased as their values increased for both PLASSIM emitter and Heping emitter.

(3) Soil physical properties of light sand soil was the most susceptible to the changes in bulk density and initial soil water content. In case of high soil water content, the flow rate of light sand decreased with the fastest rate as bulk density increased. In case of low soil water content, flow rate of light clay soil was the lowest and that of light sand soil was the highest.

Figure 6. $\partial q_{SDI}/\partial \gamma$ as a function of bulk density.
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