Experimental study on calculation model of labyrinth emitter discharge under subsurface drip irrigation

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Abstract: For different texture of soils, the grain composition is different with significant changes. Since the emitter of subsurface drip irrigation (SDI) is buried in the soil, emitter discharge is influenced by soil properties. An experiment was conducted to investigate the relationship between the soil properties with emitter working pressure and emitter discharge of SDI. Selecting three different grain composition soils, and emitter working pressure, as well as soil clay content, soil bulk density and initial soil moisture content respectively as influence factors of emitter discharge of SDI, the experimental scheme was gained by uniform design. A calculation model for determination of the SDI emitter discharge was established by regression analysis with the first two kinds of soil test data, and its reliability was verified by the third kind of soil test data. The model is simple with high accuracy, easy to use, and lays the foundation to study hydraulic elements of SDI field network, especially taking the soil clay content as an influencing factor has widened the scope of application of the model. The achievement is of great significance for design and management of SDI.

Keywords: subsurface drip irrigation, emitter, soil clay content, discharge, calculation model
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1 Introduction

Nowadays, water resources have become a strategic problem related to regional subsistence and development in China[1]. Subsurface drip irrigation (SDI) is now becoming a common irrigation method for crops, trees and landscape. It also has a much higher yield and capability for minimizing the loss of water by evaporation, runoff, and deep percolation compared with those traditional irrigation systems[2]. Subsurface drip irrigation is the most advanced irrigation technology to provide water and nutrients into root zone of the plants through the emitters and laterals buried below the soil to maintain the soil surface dry[3-6].

One of the differences between subsurface drip irrigation and surface drip irrigation is that the emitter flow rate of subsurface drip irrigation will be affected by the soil physical properties[7-9]. To determine emitter discharge of SDI is the main basis in drip irrigation engineering design. Lazarovitch et al.[10] introduced a new approach for predicting discharge in SDI laterals. They established a coupled model to evaluate the performance of SDI laterals while changing the inputs, such as the lateral diameter, length and slope, emitter nominal discharge and exponent, inlet pressure head, soil hydraulic properties and soil spatial variability. Gil et al.[11] proposed an experiment to measure the emitter discharge and pressure at the emitter outlet in different soils. They observed the SDI emitter discharge

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decreased, and a procedure which determined emitter maximum flow rate was raised to select emitter discharge on different soils considering the effect of soil hydraulic properties. Gil et al.[12] measured various emitter discharges carried out in containers with uniform loamy soils, and established the relationship between soil pressure and emitter discharge to explain the capacity of the emitter buried in soil. Emitter structure, emitter working pressure and soil physical properties are just some of the main influence factors on SDI emitter discharge. Once emitter is selected, it turns out that the major factors influencing the emitter discharge are emitter working pressure and soil physical properties.

It was found that emitter discharge buried in soil is less than that of free outflow[13]. When the soil surrounding SDI emitter formed a saturated zone, it was to generate certain positive pressure at the emitter outlet, and as a result, the emitter discharge reduced[14-15]. The SDI emitter discharge was larger at the beginning, but gradually decreased to stabilization and it just lasted a few minutes. Accordingly, a method was proposed to calculate SDI emitter discharge with some of theoretical foundation, while the positive pressure may be not easily determinable.

For convenience of application in engineering, a new calculation model was put forward to determine SDI emitter discharge, in which the emitter working pressure, initial soil moisture content and soil bulk density were viewed as factors on the basis of the test[15]. The results show that the simplified model is similar to the formula of surface drip irrigation discharge calculation, whereas the experience parameter was obtained directly at a kind of soil test. Actually, the grain composition of different texture of soil is of great variability, and even the same texture is not entirely the same grain composition. Consequently, the formula is of lower suitability.

The main objective of this research was to establish a calculative formula for SDI emitter discharge with a simple form, easy calculation and better common applicability for soils.

2 Materials and methods

2.1 Materials

Three kinds of tested soils were provided in the experiment. Referred to the soil texture classification standards, they were light clay soil, silt loam soil and light sandy soil, and the soil granular analysis were achieved through computer data processing (Table 1).

Table 1 Soil granular analysis of three tested soils

Soils	Soil particles volume/%							
	Particle size/mm							
	<1.000	<0.500	<0.250	<0.100	<0.050	<0.010	<0.005	<0.001
Light clay soil	99.98	99.12	98.3	92.96	65.37	52.76	36.96	32.02
Silt loam soil	99.6	99.2	98.87	98.6	89.15	28.02	11.34	0.9
Light sandy soil	99.97	99.34	98.45	95.91	45.66	19.87	11.47	0.11

Since the emitter is buried in soil, emitter discharge is very small and hard to measure. Wang et al.[16] have introduced a new test method which built up an experiment system of SDI lateral in the laboratory to achieve the emitter discharge. The basic test principle is weighing method. The test system consists of weighing sensors, pressure sensors, data acquisition system, and a personal computer. The system can not only synchronously and indirectly measure the discharge of emitters and directly measure the pressure of branch pipes and laterals of SDI pipe network in the laboratory, but also realize the function of automatic monitoring, collecting and storing test data. The measured results show that the accuracy of the test system can meet the experiment requirements, and it is easy to operate.

In the laboratory, the drip irrigation pipes connected with branch pipe go through the soil barrels to guarantee the emitters inside of the drip irrigation pipes were buried in. The external diameter of soil barrel is 40 cm, and the design emitter buried depth is 20 cm. Initial soil moisture content is determined by drying method. With emitters in barrels flowing out, weighing sensor can measure the weight of soil barrels at different times, and the change of weight is added value of emitter water at different time periods. The emitter discharge can be easily calculated. The pressure transmitter was installed on the drip irrigation pipe before the soil barrel could directly measure the emitter working pressure.

The experimental emitter is the turbulence labyrinth embedded-style drip irrigation line. The external diameter of the drip irrigation tube is 14.70 mm, of which the internal diameter is 12.70 mm, and the rated flow of the emitter is 2.00 L/h.

The relationship between water pressure head and emitter discharge of surface drip irrigation can be expressed in the following equation:

$$q_{DI} = 0.1687H^{0.5390} \tag{2}$$

where, q_{DI} represents emitter discharge under surface drip irrigation, L/h; H is emitter working pressure of surface drip irrigation, kPa. The determination coefficient of Equation(2) is 0.9997.

2.2 Experimental schemes

For the three kinds of tested soils, three experiment factors were chosen, which were emitter work pressure, soil bulk density and initial soil water content. According to actual engineering, the value of working pressure is between 60-370 kPa; and that of soil bulk density is between 1.25 and 1.40 g/cm^3; the range of initial soil moisture content is 12%-18% (mass basis), and the emitter depth is at 30 cm.

It should be divided into a number of standards at each value range of three factors for every soil, while if do as overall design scheme, test workload is too much. In order to reduce the amount of experiment times and achieve more information, mixed uniform design should be needed. Each soil needs 8 groups of experiment, and three soils need 24 groups of experiment (Table 2).

Table 2 Experiment scheme of uniform design

Test number	Combinations of factor and standard		
	Emitter working pressure/kPa	Soil bulk density /g cm^{-3}	Initial soil moisture content/%
1	60	1.35	18
2	100	1.25	16
3	150	1.35	14
4	200	1.25	12
5	250	1.40	18
6	300	1.30	16
7	350	1.40	14
8	370	1.30	12

3 Results and discussion

Because the time that emitter discharge of SDI reaches steady is too short, emitter stabilization discharge is set as the design basis. Thus, emitter stabilization discharge of SDI should be obtained (Table 3).

Table 3 Test results

Soil	Test number	Clay content/%	Working pressure/kPa	Soil bulk density/g cm^{-3}	Initial soil moisture content/%	Emitter discharge/L h^{-1}
Light clay soil	1	52.76	65.80	1.35	18.58	1.3010
	2	52.76	105.86	1.25	15.91	1.7690
	3	52.76	157.61	1.35	13.56	2.2980
	4	52.76	203.76	1.25	12.52	2.6270
	5	52.76	259.03	1.40	17.38	2.9770
	6	52.76	305.01	1.30	16.02	3.2630
	7	52.76	345.77	1.40	13.48	3.4970
	8	52.76	372.90	1.30	11.98	3.7600
Silt loam soil	1	28.02	63.43	1.35	17.77	1.3200
	2	28.02	105.28	1.25	16.10	1.7730
	3	28.02	155.64	1.35	13.95	2.2170
	4	28.02	198.67	1.25	12.16	2.6470
	5	28.02	252.12	1.40	17.69	2.8880
	6	28.02	299.66	1.30	16.10	3.2830
	7	28.02	356.20	1.40	13.93	3.6780
	8	28.02	372.13	1.30	12.18	3.8310
Light sandy soil	1	19.87	62.47	1.35	18.26	1.2940
	2	19.87	104.35	1.25	15.97	1.7570
	3	19.87	153.52	1.35	14.23	2.2730
	4	19.87	202.86	1.25	12.21	2.7560
	5	19.87	250.17	1.40	17.96	2.9220
	6	19.87	300.40	1.30	16.20	3.3730
	7	19.87	352.39	1.40	13.66	3.7010
	8	19.87	371.30	1.30	12.12	4.0190

Based on the study of a lot of experimental results, <0.01 mm clay content is an important incident in soil granularity composition, and has a great influence on the properties of the soil, such as plasticity, swelling, hygroscopicity and permeability, and it is an clear limit in maximum molecular moisture capacity. Therefore, <0.01 mm clay content is regarded as an element which affects emitter discharge of SDI (Table 3).

Judged by the experimental results, value of emitter discharge is influenced by clay content, working pressure, soil bulk density and initial soil moisture content. The change of any single factor can cause the difference of emitter discharge.

4 Calculation model

4.1 Establishment of calculation model

As mentioned above, emitter discharge in SDI can be affected by soil properties and water pressure head. Selection of design variables (<0.01 mm clay content, soil bulk density, initial soil moisture content, and working pressure) and SDI emitter discharge could be estimated by the calculation model.

$$q=kM^a\gamma^b\theta^c H^x \tag{3}$$

where, q is emitter discharge of SDI, L/h; M is <0.01 mm clay content, %; γ is soil bulk density, g/cm^3; θ is initial soil moisture content, %; H is emitter working pressure under subsurface drip irrigation, kPa; k is empirical coefficient; a, b, c and x are experiential indices, respectively.

Both sides of Equation (3) are taken logarithm.

$$\ln q=\ln k+a\ln M+b\ln\gamma+c\ln\theta+x\ln H \tag{4}$$

Some simple unknown letters are selected to represent the complex logarithmic.

$$\begin{aligned} &Y=\ln q, K=\ln k, X_1=\ln M,\\ &X_2=\ln\gamma, X_3=\ln\theta, X_4=\ln H \end{aligned} \tag{5}$$

And then Equation (3) can be changed into multiple linear regression issue.

$$Y=K+aX_1+bX_2+cX_3+xK_4 \tag{6}$$

In accordance with the 16 groups of data under light clay and silt loam, the value of k, a, b, c, and x can be obtained by regression calculation. And then substitute them into Equation (3):

$$q=0.16M^{-0.0185}\gamma^{-0.0546}\theta^{-0.0884}H^{0.5839} \tag{7}$$

4.2 Verification and analysis of calculation model

The determination coefficient of Equation (7) is 0.9991, and the significant test value F is 3067.53, which indicate that the calculation model has a high correlation.

By substitution of the 8 groups of data including clay content, working pressure, soil bulk density and initial soil moisture content of light clay into Equation (7), calculated value of discharge under SDI is obtained (Table 4). The maximum relative error is 4.84%, the precision of which can satisfy the requirements of engineering design.

Table 4 Comparison between calculated and experimental values of emitter discharge in light clay under SDI

Test number	1	2	3	4	5	6	7	8
Experimental value/L h^{-1}	1.2940	1.7570	2.2730	2.7560	2.9220	3.3730	3.7010	4.0190
Calculated value/L h^{-1}	1.3000	1.7825	2.2466	2.6910	2.9213	3.2937	3.6556	3.8244
Error/%	0.46	1.45	1.16	2.36	0.03	2.35	1.23	4.84

4.3 Influence analysis on factors of SDI

On the basis of range of each influence factors, the mean values of soil clay content, soil bulk density, initial soil moisture content and working pressure are 36.22%, 1.33 g/cm^3, 15% and 218 kPa, respectively, which are set as reference values. Change rate of each influence factor is -10%−10%, then DI emitter discharge is calculated by putting these factors into Equation (7).

Table 5 states that an increase in SDI emitter discharge is usually accompanied by a rise of working pressure, a decrease in soil clay content, a depression of bulk density, and a reduction in initial soil moisture content. The effect degree of each factor on SDI emitter has been ranked: working pressure>initial soil moisture content>soil bulk density>soil clay content.

Table 5 Influence of each factor on SDI emitter (L h^{-1})

Change rate/%	Clay content/%	Soil bulk density/g cm^{-3}	Initial soil moisture content/%	Working pressure/kPa
-10	2.7201	2.7305	2.7402	2.5528
-5	2.7174	2.7224	2.7271	2.6347
0	2.7148	2.7148	2.7148	2.7148
5	2.7123	2.7076	2.7031	2.7932
10	2.7100	2.7007	2.6920	2.8702
Emitter discharge changeable range	-0.0101	-0.0298	-0.0482	0.3174

4.4 Comparison between DI and SDI emitter discharge

Figure 1 depicts calculated value of DI and SDI emitter discharge under different work pressure according to Equations (2) and (7) when soil clay content, soil bulk density and initial soil moisture content were 36.22%, 1.33 g/cm^3 and 15%, respectively.

From Figure 1, it is apparent that DI emitter discharge is greater than SDI emitter discharge, and the larger pressure, the larger difference of the above two.

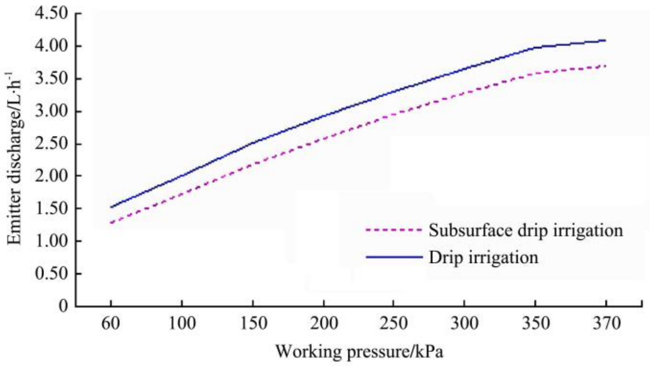

Figure 1 DI and SDI emitter discharge under different working pressures

4.5 Calculation example

Substituting the appropriate values for emitter of turbulence labyrinth embedded-style drip irrigation line under subsurface drip irrigation, the soil clay content is 44%, soil bulk density is 1.33 g/cm^3, initial soil moisture content (mass basis) is 13%, the working pressure is 100 kPa, and the value of emitter discharge can be determined by the calculation model (Equation (7)), which is 1.74 L/h.

5 Conclusions

Based on the investigation, it can be concluded that:

1) The establishment of calculation model to calculate emitter discharge under subsurface drip irrigation could be a useful tool for design, especially that soil clay content was chosen to be one of the influence factors that improves the applicability of the model, with its simple form, easiness of calculating and the calculation accuracy of which can meet the design requirement.

2) Except soil clay, some elements were selected to determine SDI emitter discharge, such as working pressure, soil bulk density and initial soil moisture content.

3) The findings of the study also suggested that the larger the working pressure, the greater the emitter discharge, while the larger the soil clay content, bulk density or initial soil moisture content, the smaller the emitter discharge. Moreover, the effect sequences of these factors for emitter discharge are as follows: working pressure, initial soil moisture content, soil bulk density and soil clay content.

4) Furthermore, the value of emitter discharge under surface drip irrigation is greater than that of SDI emitter discharge, and the higher the pressure, the larger the difference of the above two.

In this study, the calculation model of emitter discharge under SDI is only applied to the turbulence labyrinth embedded-style drip irrigation line. For other kinds of drip irrigation, it remains to be studied, but the theory and methodology can provide a useful reference.

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