Simplified method for designing diameter of drip irrigation laterals based on emitter flow variation

Ju Xueliang[1,2], Wu Pute[1,2※], Weckler R. Paul[3], Zhu Delan[2], Zhang Lin[1,2]

(1. *Institute of Soil and Water Conservation, Northwest A&F University, Yangling* 712100, *China*;
2. *Institute of Water Saving Agriculture in Arid Areas of China, Northwest A&F University, Yangling* 712100, *China*;
3. *Department of Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater* 74078, *USA*)

Abstract: A simple, direct, and easily adaptable analytical approach was developed for determining the appropriate diameter of the drip laterals laid on uniformly sloping grounds. The emitter flow variation was used as the index of water application uniformity. A diameter design parameter was developed by reformulating the analytical expressions of emitter flow variation of the single inlet lateral and paired laterals. The relationship between parameter and pressure loss ratio were expressed by the graphs and formulas. For the specific value of velocity exponent, the condition for designing the diameter of a single inlet lateral was the calculation parameter lying between -1 and ≤2.801, between -1 and ≤2.859 and between-1 and ≤4, respectively; meanwhile, the condition for designing the diameter of the paired laterals was the calculation parameter lying between 0 and ≤3.143, between 0 and ≤3.183 and between 0 and ≤4, respectively. On the other hand, for the required emitter flow variation and emitter design discharge, there would be one or two solutions of diameter for a single inlet lateral, and one, two or numerous solutions for the paired laterals. Based on the ranges of the parameter, the design equations for the diameter of the single inlet lateral and paired laterals were derived with the pressure loss ratio as the design variable. The analytical expressions of inlet working pressure head of drip laterals were also simplified based on the energy gradient line method. When the emitter design flow, emitter flow variation criterion, and lateral length were provided, the diameter and inlet working pressure head of the drip laterals could be easily calculated without performing complex computer operations or tedious computations. In case 1, the differences in the designed parameters of a single inlet lateral from the proposed approach and variable discharge method are less than 4% for most ground slopes. In case 2, the maximum deviation in the design parameters of the paired laterals from the proposed approach and previous two methods was ≤4%. These 2 cases indicated that the proposed approach could produce accurate results as those of the previous methods for practical purposes. By using the developed analytical expressions and regression relationships, the proposed approach provided a more simplified and adaptable design procedure than the traditional methods. This research could provide valuable information for improving the hydraulic design of drip irrigation system.

Keywords: irrigation; nozzles; flow rates; drip irrigation; emitter flow variation; diameter; analytical technique
doi：10.11975/j.issn.1002-6819.2016.05.002
CLC number: S275.6 **Document code:** A **Article ID:** 1002-6819(2016)-05-0014-07

Ju Xueliang, Wu Pute, Weckler R. Paul, Zhu Delan, Zhang Lin. Simplified method for designing diameter of drip irrigation laterals based on emitter flow variation[J]. Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE), 2016, 32(5): 14－20. (in English with Chinese abstract) doi：10.11975/j.issn.1002-6819.2016.05.002 http://www.tcsae.org
鞠学良，吴普特，Weckler R. Paul，朱德兰，张 林. 基于流量偏差率的滴灌毛管管径简易设计[J]. 农业工程学报，2016，32(5)：14－20. doi：10.11975/j.issn.1002-6819. 2016.05.002 http://www.tcsae.org

0 Introduction

The main objective in drip irrigation design is the uniform distribution of water delivered through the emitters on the lateral line. Numerous procedures have been developed for the hydraulic design of drip irrigation laterals[1-26].

Determining the appropriate size of a drip irrigation lateral below a specified level of water application uniformity is a common hydraulic design problem. Kang et al[11] elaborated a simplified approach to design drip irrigation systems using the lateral flow rate equation concurrently with back step and forward step approaches. Analytical results show that the diameter for the required Christiansen's uniformity coefficients (C_U) may have 2 solutions when laterals are laid on sloped fields. Ravikumar et al.[15] developed an analytical approach for direct design of the lateral diameter by writing the analytical equation of coefficient of variation of discharge (C_{Vq}) in quadratic form. 2 diameters of the laterals may be produced for some certain

Received date: 2015-07-29 Revised date: 2016-01-18
Foundation item: National Key Technology Research and Development Program of the Ministry of Science and Technology of China (2015BAD22B01-02); National International Cooperation in Science and Technology Special Program (2014DFG72150); 111 Project (B12007)
Biography: Ju Xueliang, PhD. Candidate, Major in the field of water saving theory and technology. Yangling Institute of Soil and Water Conservation, Northwest A&F University, 712100. Email: juxueliang1987@nwsuaf.edu.cn. Memeber of CSAE: Ju Xueliang (E040000434A)
※Corresponding author: Wu Pute, researcher, Major in the field of water saving theory and technology. Yangling Institute of Soil and Water Conservation, Northwest A&F University, 712100. Email:gjzwpt@vip.sina.com

design situations.

In China, according to the Chinese technical standard for micro-irrigation engineering (GB/T 50485-2009)[21], emitter flow variation (q_v) was chosen as the only design uniformity index for the hydraulic design of micro-irrigation systems. Zhang[7] developed analytical equations of q_v for a single inlet drip irrigation lateral for 3 pressure profile types based on energy-gradient-line (EGL) approach. By using the implicit equations, the diameter of single inlet laterals could be determined based on the trial and error technique or the iterative procedure. Ju et al[24] developed the analytical equations q_v for paired drip irrigation laterals laid on uniformly sloping ground based on the EGL approach. The solutions of the design equations of the diameter of the paired laterals are also dependent on the trial and error technique or the iterative procedure.

Although the solutions of the implicit equations can be easily obtained by Excel Equation-Solver or some other software packages, it can produce only 1 diameter for the specified level of q_v. To the best of our knowledge, no research has been published for determining the appropriate size (especially 2 or more solutions if necessary) of drip irrigation laterals based on emitter flow variation q_v.

In this paper, a simplified method for determining the diameter of uniformly sloping drip irrigation laterals was developed by reforming the analytical equations of emitter flow variation. The following assumptions were made in developing the proposed analytical approach: 1) All emitters were equally spaced and had equal discharge; 2) Hydraulic characteristics (e.g., pipe friction factor and pipe diameter) remained constant along the entire length of the paired laterals; 3) The velocity head along the lateral was neglected; and 4) The ground slope was fairly uniform. This research could provide theoretical basis for improving the hydraulic design of drip irrigation system.

1 Methods and design procedure

1.1 Design method of parameters

1.1.1 Design equations of diameter for a single inlet lateral

Assuming that the system's hydraulic characteristics and the ground slope are the only factors affecting the water application uniformity, the pressure head variation occurs due to the combined effect of friction head losses and the changes in elevation[23-27]. Based on the EGL method, the analytical expression of emitter flow variation of a single inlet lateral could be expressed as[22]

$$q_v = \lambda_s \cdot \frac{x \cdot \Delta H_F}{h_d} = \frac{\lambda_s}{J} \cdot \frac{x \cdot \Delta H_S}{h_d}, \tag{1}$$

$$\lambda_s = \begin{cases} 1-J & J<0 \\ 1-J+c_2 \cdot J^{c_1} & 0 \leqslant J<1 \\ c_2 \cdot J^{c_1} & 1 \leqslant J<m+1 \\ J-1 & J \geqslant m+1 \end{cases}, \tag{2}$$

where λ_s is the dimensionless parameter for calculating emitter flow variation q_v of a single inlet lateral; x is emitter exponent; h_d is the design emitter pressure head, m; ΔH_F is the total energy losses by friction along the lateral, $\Delta H_F=F_C \cdot F_S \cdot K \cdot Q_0^m/(D^b \cdot L)$, F_C is Christiansen's correction coefficient for friction head loss computation in finite number of multiple outlet pipes[27]; F_S is amplification factor to be applied to the friction losses in the uniform lateral sections accounts for the effect of local energy losses due to emitter connections, value is 1.10-1.20[27]; Q_0 is total flow rate for the entire length of the lateral, L/h, $Q_0=N.\ q_d$; N is the total number of equally spaced emitters for the entire lateral, $N=(L-s_1)/s_e+1$; s_e is emitter spacing, m; s_1 is inlet spacing, m; q_d is the design emitter discharge, L/h; D is the internal diameter of the lateral, mm; K is the combined units coefficient and roughness coefficient; m and b are the velocity and diameter exponents, respectively. The values of coefficients m, b and K under different flow regime can be founded at GB/T 50485–2009[27]. c_1 and c_2 are calculation parameters[24]. For m=1.75, c_1=1.571 and c_2=0.357; for m=1.69, c_1=1.592 and c_2=0.350; for m=1.00, c_1=2.00 and c_2=0.25. J is the pressure loss ratio which is the function of diameter, $J=\Delta H_S/\Delta H_F$; ΔH_S is energy gain or loss due to slopes, m, $\Delta H_S=p \cdot S_0 \cdot L$; S_0 is the ground slope assumed to be uniform along the lateral, %; p is the signal symbol, for uphill ground, $p=-1$; for level ground, p=0; for downhill ground, p=1.

In order to design the diameter of a single inlet lateral, Eq.(1) was reformulated by

$$\frac{x \cdot \Delta H_S}{q_v \cdot h_d} = W = \frac{J}{\lambda_s}, \tag{3}$$

where W is the parameter design which can be calculated by the known x, ΔH_S, q_v and h_d, dimensionless.

In Eq.(3), based on the definition of parameters, only J and λ_s are the functions of diameter. With the given design parameter, the diameter can be determined by the solving of Eq.(3).

For the level ground, submitting λ_s =1 into Eq.(1), and rearranging, the diameter of a single inlet lateral could be easily calculated by

$$D = \left(\frac{x \cdot M}{q_v \cdot h_d} \right)^{1/b}, \tag{4}$$

where M is the calculation parameter, which is independent with diameter, $M=F_C \cdot F_S \cdot K \cdot Q_0^m \cdot L$.

For a nonzero uniformly sloping lateral, based on the definition of J, the diameter could be formulated by

$$D = \left(\frac{M}{\Delta H_S} \cdot J \right)^{1/b}. \tag{5}$$

For an uphill lateral, J <0; Submitting $\lambda_s=1-J$ into Eq.(3) and rearranging, J could be written as

$$J = \frac{W}{W+1}. \tag{6}$$

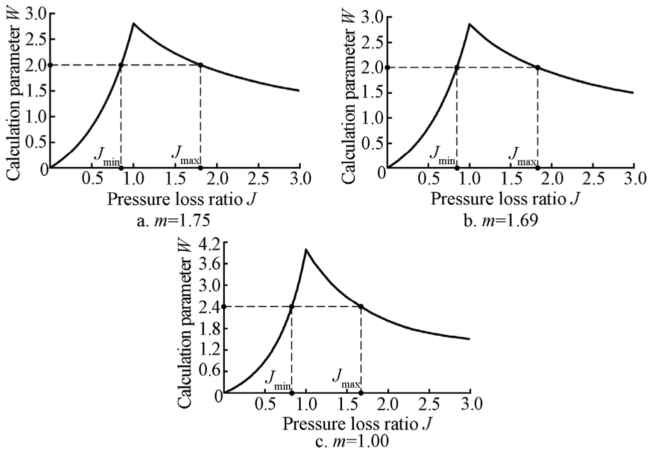
Submitting Eq.(6) into Eq.(5), the diameter of a single inlet lateral laid on uphill ground could be simplified calculated by

$$D = \left(\frac{M}{\Delta H_S} \cdot \frac{W}{W+1} \right)^{1/b}. \tag{7}$$

According to Eq.(7), the condition for designing the diameter of an uphill lateral should satisfy that: $-1<W<0$.

For a single inlet lateral laid on downhill ground, based on Eq.(2), the formulations of diameter were the implicit functions that could not be analytical expressed. However, similar with the situation of uphill ground, the solutions of diameter may be also determined by analysis of the relationships between W and J.

Based on Eq.(2) and Eq.(3), the relationships between W and J for different m of a single inlet lateral laid on downhill ground are shown in Fig.1.



Note: J_{min} and J_{max} are pressure loss ratios corresponding to minimum and maximum diameter; m is velocity exponent.

Fig.1 Relationships between diameter design parameter W and pressure loss ratio J of a single inlet lateral laid on downhill ground

From Fig.1, it could easily explain that there would be 1 or 2 solutions for a single inlet lateral laid on downhill ground for the required water application uniformity[11]. Based on Fig.1, Eq.(2) and Eq.(3), the solutions distribution of diameter for a single inlet lateral laid on downhill ground was summarized in Table 1.

Table 1 Number of diameter solutions for single inlet lateral laid on downhill ground

Range of diameter design parameter W		Solutions of pressure loss ratio J	Solutions number of diameter D
Low limit	Upper limit		
0	≤1	J_{min}	1
1	$<1/c_2$	J_{min}, J_{max}	2
$1/c_2$	$1/c_2$	1	1
$>1/c_2$		-	-

Note:"-" means no solution, then condition for designing diameter of a downhill lateral should satisfy that W was ≤2.801, ≤2.859, and ≤4 for velocity exponent of 1.75, 1.69, and 1.00, respectively.

With the known W, Fig.1 could be used for determining the values of J under most design situations of the single inlet lateral. Then, the diameter could be calculated based on Eq.(5) with the known J.

Furthermore, the design equations of J_{max} and J_{min} for different m of a single inlet downhill lateral were developed based on Eq.(2) and Eq.(3) by analytical method and numerical fitting technique.

The design equation of J_{max} for a single inlet lateral laid on downhill ground could be analytical expressed by

$$J_{max}=\begin{cases}(m+1)\cdot\left(c_1\cdot W^{-1}\right)^m & c_1<W<c_2^{-1}\\ W\cdot(W-1)^{-1} & 1<W\leqslant c_1\end{cases}. \tag{8}$$

Meanwhile, when m=1, the design equation of J_{min} for a single inlet downhill lateral could also be analytical expressed by

$$J_{min}=2\left[W^{-1}+1-\sqrt{\left(W^{-1}+1\right)^2-1}\right]. \tag{9}$$

On the other hand, for m=1.69 or 1.75, the design equations of J_{min} for a single inlet downhill lateral were developed by regression analysis method with the numerical fitting technique (Table 2).

Table 2 Regression equations of design parameter J_{min} as diameter design parameter W with velocity exponent 1.75 and 1.69 for a single inlet lateral laid on downhill ground

Velocity exponent m	Range of diameter design parameter W		Regression equations	Regression coefficient R^2
	Lower limit	Upper limit		
1.75	0	≤0.25	$J_{min}=(W^{-1}-0.3146W^{0.5429}+1)^{-1}$	0.9999
	0.25	≤0.50	$J_{min}=(W^{-1}-0.272W^{0.4527}+1)^{-1}$	0.9999
	0.50	≤1.00	$J_{min}=(W^{-1}-0.2611W^{0.3922}+1)^{-1}$	0.9999
	1.00	≤1.571	$J_{min}=(W^{-1}-0.2606W^{0.336}+1)^{-1}$	0.9999
	1.571	≤2.801	$J_{min}=(W^{-1}-0.2671W^{0.2843}+1)^{-1}$	0.9999
1.69	0	≤0.25	$J_{min}=(W^{-1}-0.3066W^{0.5619}+1)^{-1}$	0.9999
	0.25	≤0.50	$J_{min}=(W^{-1}-0.2633W^{0.4677}+1)^{-1}$	0.9999
	0.50	≤1.00	$J_{min}=(W^{-1}-0.2523W^{0.4044}+1)^{-1}$	0.9999
	1.00	≤1.592	$J_{min}=(W^{-1}-0.2518W^{0.3452}+1)^{-1}$	0.9999
	1.592	≤2.859	$J_{min}=(W^{-1}-0.2586W^{0.2904}+1)^{-1}$	0.9999

For all the determination coefficient R^2 in Table 2 were not less than 0.9999, indicating that the regression equations were sufficiently accurate to calculate the J_{min} for a single inlet lateral laid on downhill ground. All the design equations were easy-to-use for designing the single inlet lateral.

1.1.2 Design equations of diameter for paired laterals

Based on the EGL method, the analytical expression of emitter flow variation of paired laterals was developed as[24]

$$q_v=\lambda_p\cdot\frac{x\cdot\Delta H_F}{h_d}=\frac{\lambda_p}{J}\cdot\frac{x\cdot\Delta H_S}{h_d}, \tag{10}$$

$$\lambda_p=\begin{cases}R_L^{m+1}+R_L\cdot J & 0\leqslant J\leqslant\left(1-R_L\right)^m\\ \dfrac{1}{2c_1}\cdot J & \left(1-R_L\right)^m<J\leqslant\dfrac{m+1}{2^m}\\ c_2\cdot J^{c_1} & \dfrac{m+1}{2^m}<J\leqslant 2\times\dfrac{m+1}{m+2}\end{cases}, \tag{11}$$

$$\left(1-R_L\right)^{m+1}-R_L^{m+1}=\frac{J}{2}\cdot\frac{m+2}{m+1}, \tag{12}$$

where λ_p is the dimensionless parameter for calculating emitter flow variation q_v of paired laterals; R_L is the dimensionless parameter of best manifold position, $R_L=L_{up}/L$; L_{up} is the length of the uphill part of the paired laterals, m.

In order to design the diameter of paired laterals, Eq.(10) was reformulated in the same form with Eq.(3) as

$$\frac{x\cdot\Delta H_S}{q_v\cdot h_d}=W=\frac{J}{\lambda_p}. \tag{13}$$

For the level ground, R_L=0.5, $\lambda_p=0.5^{m+1}$, thus, the diameter of the paired lateral could be expressed by reformulating Eq.(10) as

$$D=\left(\frac{1}{2^{m+1}}\cdot\frac{x\cdot M}{q_v\cdot h_d}\right)^{1/b}. \tag{14}$$

For the nonzero uniformly sloping paired laterals, the diameter could also be calculated by Eq.(5). The solutions of diameter could also be determined by analysis of the relationships between W and J.

Combining Eq.(11) and Eq.(13), the relationships between W and J for different m of paired laterals are shown in Fig.2.

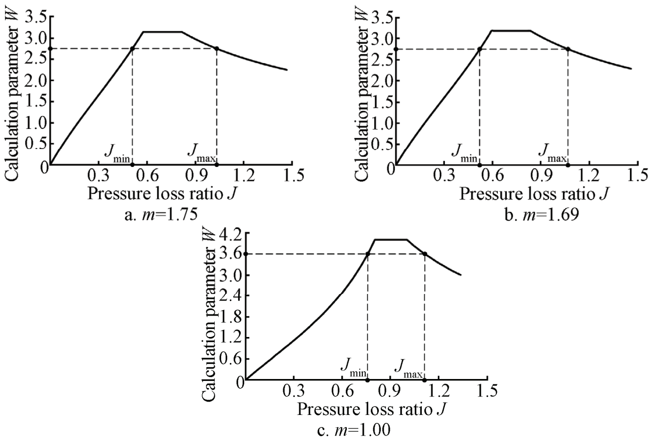


Fig.2 Relationships between diameter design parameter W and pressure loss ratio J of paired laterals laid on uniformly sloping ground

From Fig.2, there may be 1, 2 or many solutions for paired laterals laid on uniformly sloping ground for the required emitter flow variation and emitter design discharge. Based on Fig.2, Eq.(11) and Eq.(13), the number of diameter solutions for paired laterals laid on uniformly sloping ground was summarized in Table 3.

Table 3 Number of diameter solutions for paired laterals laid on uniformly sloping ground

Range of diameter design parameter W		Solutions of pressure loss ratio J	Solutions number of diameter D
Lower limit	Upper limit		
0	$<(0.5m+1)^{1/m}\cdot c_1$	J_{min}	1
$\geqslant(0.5m+1)^{1/m}\cdot c_1$	$<2c_1$	J_{min}, J_{max}	2
$2c_1$	$2c_1$	J_{min}–J_{max}	numerous
$>2c_1$		-	-

Note: the condition for designing the diameter of paired laterals should satisfy that: $W\leqslant3.143$ for m=1.75; $W\leqslant3.183$ for m=1.69; $W\leqslant4$ for m=1.00.

With the known W, Fig.2 could be used for determining the values of J of paired laterals. Then, the diameter of paired laterals could be calculated based on Eq.(5) with the known J.

Moreover, the design equations of J_{max} and J_{min} for different m of paired laterals were developed based on Eq.(11), Eq.(12) and Eq.(13) by analytical method and numerical fitting technique.

From Fig.2, when $W=2c_1$, there would be many solutions of J satisfying the requirement of water application uniformity. The solutions range of J were expressed by

$$(1-R_L)^m\leqslant J\leqslant 2^{-m}(m+1). \tag{15}$$

When $W<2c_1$, there would be 1 or 2 solutions of J. The design equation of J_{max} for paired laterals could be analytical expressed by

$$J_{max}=(m+1)\cdot\left(c_1\cdot W^{-1}\right)^m \quad (0.5m+1)^{1/m}\cdot c_1\leqslant W<2c_1. \tag{16}$$

Meanwhile, when m=1, the design equation of J_{min} for paired laterals could also be analytical expressed by

$$J_{min}=\frac{8W-64}{30W}+\sqrt{\left(\frac{64-8W}{30W}\right)^2+\frac{16}{15}} \quad 0<W\leqslant4. \tag{17}$$

On the other hand, for m=1.75 and 1.69, the design equations of J_{min} for paired laterals were mathematically regression analyzed by the numerical fitting technique (Table 4).

Table 4 Regression equations of design parameter J_{min} as diameter design parameter W with velocity exponent 1.75 and 1.69 for paired laterals laid on uniformly sloping ground

m	Range of diameter design diameter W		Regression equations	Regression coefficient R^2
	Lower limit	Upper limit		
1.75	0	$\leqslant2.251$	$J_{min}=0.1453W+0.0322W^2-0.0064W^3$	0.9999
	2.251	$\leqslant3.143$	$J_{min}=-0.1058+0.2712W-0.0173W^2$	0.9999
1.69	0	$\leqslant2.287$	$J_{min}=0.1526W+0.0317W^2-0.0067W^3$	0.9999
	2.287	$\leqslant3.183$	$J_{min}=-0.1009+0.2762W-0.0183W^2$	0.9999

For all the determination coefficient R^2 in Table 4 were not less than 0.9999, indicating that the regression equations were sufficiently accurate to calculate the J_{min} for paired laterals laid on uniformly sloping ground. All the design equations were easy-to-use in designing paired laterals.

1.1.3 Analytical expressions of inlet working pressure head

Inlet working pressure head h_0 is also an important parameter for designing the drip irrigation system. The analytical expressions of h_0 for the single inlet lateral and paired laterals were developed based on the EGL method[22, 24]. To simplify the design processes, the analytical expressions of h_0 of the single inlet lateral and paired laterals laid on zero and nonzero uniformly sloping ground were formulated and summarized as follows:

The inlet working pressure head h_0 of a single inlet lateral laid on the level ground can be formulated by

$$h_0\cong h_d+\frac{m+1}{m+2}\cdot\frac{M}{D^b}. \tag{18}$$

The inlet working pressure head h_0 of a single inlet lateral laid on the nonzero uniformly sloping ground can be formulated by

$$h_0\cong h_d+\frac{m+1}{m+2}\cdot\frac{M}{D^b}-\frac{1}{2}\Delta H_S. \tag{19}$$

The inlet working pressure head h_0 of the paired laterals laid on the level ground can be formulated by

$$h_0 \cong h_d + \frac{1}{2^{m+1}} \cdot \frac{m+1}{m+2} \cdot \frac{M}{D^b}. \quad (20)$$

The inlet working pressure head h_0 of the paired laterals laid on the nonzero uniformly sloping ground can be formulated by

$$h_0 \cong h_d + \frac{m+1}{m+2} \cdot \frac{M}{D^b} \cdot R_L^{m+1} + \frac{1}{2}\Delta H_S \cdot R_L. \quad (21)$$

1.2 Design procedures

1.2.1 Design procedure for diameter of single inlet lateral

When the length L, emitter spacing s_e, local energy losses amplification factor F_S, emitter hydraulic characteristics (q_d, k, x), ground slope S_0 of the single inlet lateral, and emitter flow variation criterion q_v were given, the design procedures for determining the diameter D and h_0 of the single inlet lateral based on the above-mentioned design formulas, could be outlined as followed:

1) To calculate the emitter design pressure h_d, total emitter number N, Christiansen's correction coefficient F_C, total flow rate Q_0, and the elevation changes ΔH_S, based on the known variables;

2) To calculate parameter W using Eq.(3) based on x, ΔH_S, q_v and h_d;

3) Let m=1.75, then b=4.75, K=0.505, calculate parameter $M=F_C \cdot F_S \cdot K \cdot Q_0^m \cdot L$;

4) If $W \leqslant -1$ or $W > 1/c_2$, then there will be no solutions of diameter D for the criterion of q_v; If $-1 < W < 0$, then calculate diameter D using Eq.(7) based on M, ΔH_S, W and b; If W=0, then calculate diameter D using Eq.(4) based on x, M, q_v, h_d and b; If $0 < W < 1$, calculate parameter $J_{\min}$ using the regression equations in Table 2, and calculate diameter D using Eq.(5) based on M, ΔH_S, $J_{\min}$ and b; If $1 < W < 1/c_2$, calculate parameter $J_{\max}$ using Eq.(8) based on m, c_1, c_2 and W, calculate parameter $J_{\min}$ using the regression equations in Table 2 based on W, and calculate two solutions of diameter using Eq.(5), based on M, ΔH_S, $J_{\max}$, $J_{\min}$ and b, the range of design diameter is $D_{\min} \leqslant D \leqslant D_{\max}$; If $W = 1/c_2$, J=1, then calculate diameter D using Eq.(5), based on M, ΔH_S and b;

5) To check the calculated diameter of step 4, if the solutions were greater than 8 mm, then selected the nearest commercially available standard size as the designed diameter. On the contrary, if the solutions were less than 8 mm, then let m=1.69 or 1, and repeated the steps from 3-4, until the calculated diameter satisfied the requirements of GB/T 50485-2009;

6) To calculate the inlet working pressure head h_0 using Eq.(18) or Eq.(19) based on h_d, M, D, J, m, b and ΔH_S.

1.2.2 Design procedure for diameter of paired laterals

When the length L, emitter spacing s_e, local energy losses amplification factor F_S, emitter hydraulic characteristics (q_d, k, x), ground slope S_0 of the paired laterals, and emitter flow variation criterion q_v are given, the design procedures for determining the diameter D of the paired laterals could be outlined as follows:

1) To calculate the emitter design pressure h_d, total emitter number N, Christiansen's correction coefficient F_C, total flow rate Q_0, and the elevation changes ΔH_S, based on the known variables;

2) To calculate parameter W using Eq.(3) based on x, ΔH_S, q_v and h_d;

3) Let m=1.75, then b=4.75, K=0.505, calculate parameter $M=F_C \cdot F_S \cdot K \cdot Q_0^m \cdot L$;

4) If W=0, then calculate diameter D using Eq.(14) based on m, x, M, q_v, h_d and b; If $0 < W < (0.5m+1)^{1/m} c_1$, calculate parameter $J_{\min}$ using the regression equations in Table 4, and calculate diameter D using Eq.(5) based on M, ΔH_S, $J_{\min}$ and b; If $(0.5m+1)^{1/m} \cdot c_1 \leqslant W \leqslant 2c_1$, calculate parameter $J_{\max}$ using Eq.(16) based on m, c_1, and W, and calculate parameter $J_{\min}$ using the regression equations in Table 4 based on W, and calculate two solutions of diameter using Eq.(5), based on M, ΔH_S, $J_{\max}$, $J_{\min}$ and b, the range of design diameter is $D_{\min} \leqslant D \leqslant D_{\max}$; If $W > 2c_1$, then there will be no solutions of diameter D for the criterion of q_v;

5) To check the calculated diameter of steps 4, if the solutions are greater than 8 mm, then selected the nearest commercially available standard size as the designed diameter. On the contrary, if the solutions were less than 8 mm, then let m=1.69 or 1, and repeated the steps from 3-4, until the calculated diameter satisfied the requirements of GB/T 50485－2009;

6) To calculate the pressure loss ratio J using $J=\Delta H_S \cdot D^b/M$, based on ΔH_S, D, b and M;

7) To calculate the best manifold position R_L using Eq.(12) or the regression equations from literature[24] based on m and J;

8) To calculate the inlet working pressure head h_0 using Eq.(20) or Eq.(21), based on h_d, ΔH_S, M, D, R_L, m and b.

All the design procedures could be easily realized in Microsoft Excel without any complex computer operations.

2 Approach validation

2.1 Case description

The proposed simplified approach was validated by 2 design cases covering various combinations of irrigation parameters. For the sake of comparison, the cases were also designed by other accurate methods[6,12,21].

Case 1: It was required to determine diameter D and inlet working pressure head h_0 of a single inlet drip irrigation lateral laid on downhill ground. The input data were summarized as follows: the length of the lateral L=101 m, local energy losses amplification factor F_S=1.20, the emitter spacing s_e=1.0 m, the inlet spacing s_1=1.0 m, the emitter performance equation is $q=2.54h^{0.2}$, the emitter design discharge q_d=4.0 L/h, the ground slope pS_0=0.05, the criterion of emitter flow variation q_v=0.10.

Case 2: It was required to determine diameter D, best manifold position parameter R_L and inlet working pressure head h_0 of paired laterals laid on uniformly sloping ground. The input data were summarized as follows: the length of the lateral L=89.7 m, local energy losses amplification factor F_S=1.10, the emitter spacing s_e=0.3 m, the inlet spacing s_1=0.15 m, the emitter performance equation is $q=0.411h^{0.615}$, the emitter design discharge q_d=1.50 L/h, the downhill ground slope pS_0=0.01, the criterion of emitter flow variation q_v=0.08.

2.2 Results and analysis

2.2.1 Result for case 1

According to the proposed procedure in section 1.2.1, the results of the calculation parameters were summarized. The emitter design pressure h_d=9.69 m, emitter number N=101, and Christiansen's correction coefficient F_C=0.357, total flow rate Q_0=404 L/h, and the elevation changes ΔH_S=5.05 m, diameter design parameter W=1.043. According to Table 1, there would be 2 solutions of design diameter; Assume that m=1.75, then b=4.75, K=0.505, So parameter M=794008.01, $J_{\min}$=0.590, $J_{\max}$=24.256, $D_{\min}$=11.11 mm, $D_{\max}$=24.30 mm, because $D_{\min}$>8 mm then the assumption satisfied the requirements of GB/T 50485–2009; The design diameter D should satisfy ≥11.11- ≤24.30 mm. Select the smallest commercially available standard size 12.0 mm as the design diameter. Calculate inlet working pressure head h_0=11.52 m.

For this design case, the accurate variable discharge method[12] yielded similar results for the lateral diameter: D=11.02 mm and h_0=13.83 m. However, it was difficult to design the upper limit of the diameter based on the trial and error technique.

In order to evaluate the proposed method, for various slope combinations (S_0=0, ±1%, ±2%, ±3%, ±4%), the above design parameters were solved with the same data. For comparative purposes, the results of the design parameters obtained from the proposed method and the variable discharge method are presented in Table 5.

Table 5 Assessment of proposed method with results of design case 1

Ground slope pS_0		Proposed method		Variable discharge method		Relative error in diameter D/%	Relative error in inlet pressure head h_0/%
		Diameter D/mm	Inlet pressure head h_0/m	Diameter D/mm	Inlet pressure head h_0/m		
Uphill	−0.04	18.29	12.29	16.94	12.57	7.97	−2.23
	−0.03	15.41	12.53	14.83	12.82	3.91	−2.26
	−0.02	14.03	12.77	13.67	13.07	2.63	−2.30
	−0.01	13.16	13.00	12.90	13.33	2.02	−2.48
Level	0	12.53	13.24	12.33	13.58	1.62	−2.50
Downhill	0.01	12.10	13.37	11.93	13.73	1.42	−2.62
	0.02	11.78	13.44	11.64	13.80	1.20	−2.61
	0.03	11.52	13.46	11.40	13.84	1.05	−2.75
	0.04	11.30	13.46	11.20	13.84	0.89	−2.75

From Table 5, the differences in the designed diameter from the two methods are less than 4% for most ground slopes, except for the uphill ground pS_0=−0.04, which the proposed approach produced a more conservative result than the variable discharge method. On the other hand, the differences in the design inlet pressure head from the two methods for different slopes are all less than 4%. This indicated that the proposed approach could produce the close results with those of the accurate methods for all the design situations.

2.2.2 Results for Case 2

According to the proposed procedure in section 1.2.2, the results of the calculation parameters were summarized.

The emitter design pressure h_d=8.21 m, emitter number N=300, and Christiansen's correction coefficient F_C=0.361, total flow rate Q_0=450.0 L/h, and the elevation changes ΔH_S=0.897 m, diameter design parameter W=0.840, according to Table 3, there will be only one solution of design diameter.

Assume that m=1.75, then b=4.75, K=0.505, calculate parameter M=790896.18, $J_{\min}$=0.141, $D_{\min}$=11.82 mm, because $D_{\min}$>8 mm then the assumption satisfy the requirements of GB/T 50485-2009.

The design diameter D should satisfy D≥11.82 mm. Select the smallest commercially available standard size 12.0 mm as the designed diameter.

Pressure loss ratio J=0.152, best manifold position parameter R_L=0.436, inlet working pressure head h_0=8.84 m.

For this case, the Keller method[12] yield results D=11.7 mm, R_L=0.426, h_0=8.97 m; the Wang method[21] yield results D=12.0 mm, R_L=0.457, h_0=8.83 m. The relative error in D, R_L and h_0 between the proposed approach and Keller method were 1%, 3% and −1%, respectively. Meanwhile, the relative errors in D, R_L and h_0 between the proposed approach and Wang method were −2%, −4%, and 1%. The maximum relative error in the design parameters of the paired laterals from the proposed approach and previous two methods was ≤4%. In practical perspective, the design results from the three methods were close to each other. Without performing tedious computations, the proposed approach was much easier than those of previous methods.

3 Conclusions

Based on the present research, the following conclusions were underlined:

1) A diameter design parameter W was developed by reformulating the analytical expressions of emitter flow variation. The relationship between parameter W and pressure loss ratio were expressed by the graphs and formulas. The design equations for the diameter of the single inlet lateral and paired laterals were respectively developed based on the values of W.

2) The condition for designing a single inlet lateral was −1<W≤2.801 for velocity exponent =1.75, −1<W≤2.859 for velocity exponent =1.69, −1<W≤4 for velocity exponent =1.00. Meanwhile, the condition for designing paired laterals is 0<W≤3.143 for velocity exponent =1.75, 0<W≤3.183 for velocity exponent =1.69, 0<W≤4 for

velocity exponent =1.00. For the required emitter flow variation and emitter design discharge，there would be 1 or 2 solutions of diameter for a single inlet lateral, and 1, 2 or numerous solutions for the paired laterals laid on uniformly sloping ground.

3) The proposed procedure can be applied easily for practical purposes without an excessive calculation effort. By using the proposed approach, an engineer can make the tradeoffs between the input and output parameters. The design principles of the proposed approach could also be applied for designing the optimal length of drip irrigation laterals based on emitter flow variation criterion.

[References]

[1] Howell T A, Hiler E A. Trickle irrigation lateral design[J]. Trans ASAE., 1974, 17(5): 902－908.
[2] Wu I P, Gitlin H M. Energy gradient line for drip irrigation laterals[J]. J Irrig Drain Eng, 1975, 101(4): 323－326.
[3] Gillespie V A, Phillips A L, Wu I P. Drip irrigation design equations[J]. J Irrig Drain Eng, 1979, 105(3): 247－257.
[4] Anyoji H, Wu I P. Statistical approach for drip lateral design[J]. Trans ASAE, 1987, 30(1): 187－192.
[5] Warrick A W, Yitayew M. Trickle lateral hydraulics, I: analytical solution[J]. J Irrig Drain Eng, 1988, 114(2): 281－288.
[6] Keller J, Bliesner R D. Sprinkler and Trickle Irrigation[M]. New York: Van Nostrand Reinhold, 1990.
[7] 张国祥. 微灌毛管水力设计的经验系数法[J]. 节水灌溉，1991(1)：4－8.
[8] Wu I P. Energy gradient line approach for direct hydraulic calculation in drip irrigation design[J]. Irrig Sci, 1992, 13: 21－29.
[9] Scaloppi E J, Allen R G. Hydraulics of irrigation laterals: comparative analysis[J]. J Irrig Drain Eng, 1993, 119(1): 91－115.
[10] Hathoot H M, Al-Amoud A I, Mohammad F S. Analysis and design of trickle irrigation laterals[J]. J Irrig Drain Eng, 1993, 119(5): 756－767.
[11] Kang Yaohu, Nishiyama S. Analysis and design of micro-irrigation laterals[J]. J Irrig Drain Eng, 1996, 122(2): 75－81.
[12] Valiantzas J. Analytical approach for direct drip lateral hydraulic calculation[J]. J Irrig Drain Eng, 1998, 124(6): 300－305.
[13] Hathoot H M, Al-Amoud A I, Al-Mesned A S. Design of trickle irrigation laterals considering emitter losses[J]. Irrig Drain, 2000, 49(2): 1－14.
[14] Zayani K, Alouini A, Lebdi F, Lamaddalena N. Design of drip line in irrigation systems using the energy drop ratio approach[J]. Trans ASAE, 2001, 44(5): 1051－1057.
[15] Ravikumar V, Ranganathan C R, Santhana Bosu S. Analytical equation for variation of discharge in drip irrigation laterals[J]. J Irrig Drain Eng, 2003, 129(4): 295－298.
[16] Barragan J, Wu I P. Simple pressure parameters for micro-irrigation design[J]. Biosyst Eng, 2005, 90(4): 463－475.
[17] Yıldırım G. Hydraulic analysis and direct design of multiple outlets pipelines laid on flat and sloping lands[J]. J Irrig Drain Eng, 2006, 132(6): 537－552.
[18] Zayani K, Alouini A, Souissi A. Design of drip irrigation laterals using energy drop ratio approach[J]. Trans ASAE, 2008, 51(6): 2029－2037.
[19] Yildirim G. Simplified procedure for hydraulic design of small-diameter plastic pipes[J]. Irrig Drain, 2009, 58(2): 209－233.
[20] Zayani K, Hammami M. Design of level ground laterals in drip irrigation systems[J]. J Irrig Drain Eng, 2009, 135(5): 620－625.
[21] 王新坤. 微灌系统遗传算法优化设计理论与应用[M]. 北京：中国水力水电出版社，2010.
[22] Zhang Lin, Wu Pute, Zhu Delan. Hydraulic design procedure for drip irrigation submain unit based on relative flow difference[J]. Irrigation Science, 2013, 31(5): 1065－1073.
[23] Zayani K, Hammami M, Alouini A, et al. Design of non-zero uniformly sloping laterals in trickle irrigation systems[J]. J. Irrig. Drain. Eng., 2013, 139(5): 419－425.
[24] Ju Xueliang, Weckler R Paul, Wu Pute, et al. New simplified approach for hydraulic design of microirrigation paired laterals[J]. Trans ASABE, 2015, 58(6): 1521－1534.
[25] Ju Xueliang, Wu Pute, Weckler R Paul, et al. Hydraulic design of micro-irrigation paired tapered laterals based on energy gradient line method[J]. Trans CSAM, 2015, 46(12): 47－54. (in Chinese with English abstract).
[26] Ju Xueliang, Wu Pute, Weckler R Paul, et al. Newly-simplified method for hydraulic design of micro-irrigation laterals based on emission uniformity[J]. J Drain Irrig Mach Eng, 2015, 33(8):691－700.
[27] Technical code for micro-irrigation engineering: GB/T 50485–2009[S]. Beijing: China planning press, 2009.

基于流量偏差率的滴灌毛管管径简易设计

鞠学良[1,2]，吴普特[1,2※]，Weckler R. Paul[3]，朱德兰[2]，张 林[1,2]

（1.西北农林科技大学水土保持研究所，杨凌 712100； 2. 西北农林科技大学中国旱区节水农业研究院，杨凌 712100；
3. Department of Biosystems and Agricultural Engineering, Oklahoma State University, Stillwater 74078）

摘　要：满足灌水均匀度设计标准与额定流量的滴灌毛管管径优化设计是滴灌毛管水力设计的重要内容。该文以流量偏差率为灌水均匀度设计标准，提出一种简易的滴灌毛管管径水力设计方法。通过改变单向和双向滴灌毛管流量偏差率解析公式的形式，提出一个新的管径设计参数。基于能坡线法，建立参数与坡降比参数的关系，并绘制和构建相关图形和计算公式。结果表明：当流量指数分别取值为 1.75、1.69 和 1.00 时，单向毛管管径的设计参数取值分别为−1～≤2.801，−1～≤2.859 和−1～≤4；双向毛管管径的设计参数取值分别为 0～≤3.143，0～≤3.183 和 0～≤4。满足流量偏差率设计标准和灌水器额定流量时，单向毛管管径将有 1 或 2 个设计值，双向毛管管径将有 1、2 或多个设计值。根据参数的取值范围，以坡降比参数为设计变量，推导了均匀坡下单向和双向毛管管径的计算公式。此外，进一步简化了滴灌毛管进口工作水头的计算公式。当已知设计流量，流量偏差率设计标准，毛管管长等参数时，可以按照设计步骤直接计算滴灌毛管管径和进口工作水头，无需进行任何复杂的试算。设计案例 1 表明在多数地形条件下，利用该文方法设计单向毛管的结果与传统方法设计结果的相对误差不超过 4%；设计案例 2 表明该文方法设计双向毛管的结果与其他 2 种常用方法设计结果的最大相对误差为 4%。因此，从工程实践角度，利用该方法设计的滴灌毛管管径和进口工作水头与其他传统方法设计结果非常接近。相比于传统设计方法，该方法简便实用，可以直接应用于滴灌工程设计。该研究可为改进滴灌毛管优化设计提供理论依据。

关键词：灌溉；滴头；流速；滴灌；流量偏差率；管径；解析方法