doi:10.6041/j. issn. 1000-1298. 2016. 05. 017

Appropriate Layouts of Micro-irrigation Laterals Laid on Uniformly Sloping Ground

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Abstract: The chosen of lateral layout is the basis of hydraulic design of micro-irrigation laterals. A simple and easily adaptable analytical approach was developed for the hydraulic design of micro-irrigation laterals laid on uniformly sloping grounds based on the appropriate layouts. Two indictors for comparing the emitter flow variation and inlet working pressure head from the paired layout and single downhill layout were proposed based on the analytical models of micro-irrigation laterals. By evaluating the effects of micro-irrigation laterals layouts on the emitter flow variation and working pressure head, the application condition for paired layout was suggested as the best manifold position is not less than 0. 13. When the best manifold position is less than 0. 13, the micro-irrigation lateral was proposed to use the single downhill layout in order to save the extra cost of material and installation from the paired layout. The design procedure for hydraulic design of micro-irrigation laterals was revised by considering the determination of appropriate layout. Two design cases covering various conditions indicated that the best manifold position criterion for determining the appropriate layout is more effective than the value of ground slope proposed by Keller method. The proposed approach could produce accurate results for practical purposes. This research could provide valuable information for improving the hydraulic design of micro-irrigation systems.

Key words: micro-irrigation; layout; paired laterals; analytical model

0 Introduction

The chosen of pipe layout is the basis of hydraulic design of micro-irrigation laterals. The most used layouts in field micro-irrigation systems are the single layout and paired layout[1-4]. Comparison with the single layout, the paired layout could both increase the quality of irrigation and reduce the system energy consumption. However, the paired layout needs more investments from the extra materials expenses and illustration cost. Many researches focus on the hydraulic design of micro-irrigation laterals. KELLER, et al[1], proposed the analytical expressions of best manifold position, inlet working pressure head and minimum emitter pressure head of paired laterals based on the energy gradient line (EGL) approach. JIANG, et al[5], developed a method for designing paired laterals with emitter at homologous discharge and allowable maximum and minimum emitter working pressure head were conditions needed to satisfy, based on the EGL and dichotomy method. ZHANG[6], developed an analytical approach for designing the best manifold position based on the hydraulics with limited holes in lateral. The inlet spacing ratio of uphill lateral was considered a design variable for improving the design results. BAIAMONTE, et al[7,8], developed a method for designing the best manifold position, maximum length and minimum diameter of the paired laterals. KANG, et al[9], developed a numerical method for designing the paired laterals based on finite

Received date: 2015-10-17 Accepted date: 2016-01-06

Supported by "Twelfth Five-year" National Key Technology Support Program (Grant No. 2015BAD22B01-02), International Science and Technology Cooperation Program of China (Grant No. 2014DFG72150), and Subject Innovation Engineering Program for Higher School (111 Program) (Grant No. B12007)

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element method and golden section search method. Wang, et al[10-13], proposed another numerical method for designing paired laterals based on genetic algorithms. JU, et al[14-15], developed analytical methods for designing paired laterals with single diameter and two diameters based on EGL method. The simplified analytical expressions of best manifold position, inlet working pressure head and water application uniformity indexes were developed. The design procedure of maximum length and minimum diameter of paired laterals with the single diameter or two diameters were also proposed.

KELLER, at al[1], suggested that the paired layout was only applied to the condition that the ground slope is less than 3%, however, this experience index lacks theoretical basis. Many domestic scholars suggested that for the smaller ground slope, it is prefer to apply for the paired layout, meanwhile, when the length of uphill lateral is shorter, it is prefer to apply for the single downhill layout. There were no other quantitative indexes for guiding the selection of appropriate lateral layout.

Water application uniformity and inlet working pressure head are key indexes for evaluating the quality of irrigation and system energy consumption[1]. Based on the existing hydraulic model of micro-irrigation laterals[14,16], this paper analyzed the effects of selection of paired layout and single layout on the water application uniformity and inlet working pressure head. Then, a selection criteria of the appropriate layout of micro-irrigation laterals was proposed. Furthermore, the design procedure for the micro-irrigation lateral laid on uniformly sloping ground was revised by applying the appropriate layout.

1 Analytical model of design parameters of micro-irrigation laterals

1.1 Paired laterals

Micro-irrigation paired laterals are consist of the uphill and downhill laterals. After flowing into the lateral from the manifold, water flow along the uphill and downhill laterals, respectively. 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. The design equations of emitter flow variation q_{vp} and inlet working pressure head of paired laterals h_{0p} (m) were developed based on EGL method[14]:

$$q_{vp} = \lambda_p \frac{x\Delta H_F}{h_d} \tag{1}$$

$$h_{0p} = h_d + \left(\frac{m+1}{m+2}R_L^{m+1} + \frac{1}{2}R_L J\right)\Delta H_F \tag{2}$$

in which,

$$\lambda_p = \begin{cases} R_L^{m+1} + R_L J & (0 \leqslant J \leqslant (1-R_L)^m) \\ \dfrac{1}{2c_1}J & \left((1-R_L)^m < J \leqslant \dfrac{m+1}{2^m}\right) \\ c_2 J^{c_1} & \left(\dfrac{m+1}{2^m} < J \leqslant 2\dfrac{m+1}{m+2}\right) \end{cases} \tag{3}$$

$$R_L = \frac{L_{\mathrm{up}}}{L} \tag{4}$$

$$\Delta H_F = \frac{F_C F_S K L (N q_d)^m}{D^b} \quad F_C \cong \frac{1}{m+1}$$

$$q_d = k h_d^x \quad J = \frac{\Delta H_S}{\Delta H_F} \quad \Delta H_S = S_0 L$$

$$c_1 = 1 + \frac{1}{m} \qquad c_2 = \frac{m}{(m+1)^{c_1}}$$

where, λ_p—dimensionless parameter for calculating emitter flow variation of paired laterals

x—emitter exponent

ΔH_F—total energy losses by friction along the single inlet downhill lateral with the same length of paired laterals, m

F_C—Christiansen's correction coefficient for friction head loss computation in finite number of multiple outlet pipes[17]

F_S—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, usually, it is 1.10 - 1.20[16]

K—combined units coefficient and roughness coefficient

N—total number of equally spaced emitters for the entire lateral

L—total length of the paired laterals

q_d—design emitter discharge, L/h

k—emitter flow constant coefficient

b—diameter exponent

D—internal diameter of the lateral, mm

h_d—design emitter pressure head, m

J—pressure loss ratio

ΔH_S—energy gain due to slopes along the single inlet downhill lateral with the same length of paired laterals, m

S_0—ground slope assumed to be uniform along the lateral, $S_0 \geqslant 0$

c_1, c_2—calculation parameters[14], 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 $c_2 = 0.25$

m—velocity exponent

R_L—dimensionless parameter of best manifold position

L_{up}—length of the uphill part of the paired laterals, m

The values of coefficients m, b and K under different flow regime can be determined from GB/T 50485—2009[17].

The analytical expression of parameter R_L was[14]

$$(1 - R_L)^{m+1} - R_L^{m+1} = \frac{J}{2}\frac{m+2}{m+1} \tag{5}$$

For velocity exponent $m = 1.00$, Eq. (5) could be simplified written as

$$R_L = \frac{1}{2} - \frac{3J}{8} \tag{6}$$

For velocity exponent $m = 1.75$ or $m = 1.69$, for the known pressure loss ratio J, Eq. (5) was the implicit function of parameter R_L, which could be determined by Equation Solver in Microsoft Excel. Meanwhile, Eq. (5) could be also replaced by the regression equations from Tab. 2 of Ref. [14].

In Ref. [14], three design cases illustrated that the design results from Eq. (1) and Eq. (2) were closed to those of other methods, which indicated that the accuracy of the analytical model of paired laterals.

1.2 Single downhill lateral

The single downhill lateral was a single inlet lateral perpendicular to the manifold and laid on downhill ground. Based on EGL method[16], the emitter flow variation q_{vs} and inlet working pressure head of the single downhill lateral h_{0s} (m) could be expressed by

$$q_{vs} = \lambda_s \frac{x\Delta H_F}{h_d} \tag{7}$$

$$h_{0s} = h_d + \left(\frac{m+1}{m+2} - \frac{1}{2}J\right)\Delta H_F \tag{8}$$

in which,

$$\lambda_s = \begin{cases} 1 - J + c_2 J^{c_1} & (0 \leqslant J < 1) \\ c_2 J^{c_1} & (1 \leqslant J < m+1) \\ J - 1 & (J \geqslant m+1) \end{cases} \tag{9}$$

where λ_s—dimensionless parameter for calculating emitter flow variation of a single inlet downhill lateral

2 The effect of lateral layout on the design parameters of micro-irrigation laterals

Water application uniformity and inlet working pressure head are the basic design parameters for micro-irrigation laterals. Compared with the effects of two layouts on water application uniformity and inlet working pressure head, the selection criterion of lateral layout from the points of view of irrigation quality and energy consumption are proposed.

2.1 Water application uniformity

Emitter flow variation is one of the most used index of water application uniformity[14]. In order to analysis the difference between emitter flow variation of the paired laterals and single downhill lateral, a parameter r_{qv} was defined as

$$r_{qv} = \left(1 - \frac{q_{vp}}{q_{vs}}\right) \times 100\% \tag{10}$$

Parameter r_{qv} represents the reduced percentage of emitter flow variation of paired laterals compared with that of the single downhill lateral. Obviously, the greater r_{qv}, the greater reduced percentage of q_{vp} to q_{vs}.

Substituting Eq. (1) and Eq. (7) into Eq. (10), and rearranging, r_{qv} could be expressed by

$$r_{qv} = \left(1 - \frac{\lambda_p}{\lambda_s}\right) \times 100\% \tag{11}$$

According to Eq. (3), Eq. (9) and Eq. (11), Fig. 1 showed the relationship between the parameter r_{qv} and best manifold position R_L.

From Fig. 1, when best manifold position $R_L \leqslant 0.13$, $r_{qv} = 0$, on the other hand, when $R_L > 0.13$, $r_{qv} > 0$, r_{qv} increases as the increasing R_L. For m was 1.75, 1.69 and 1.00, the maximum value of r_{qv} was 85.13%, 84.50% and 75%, respectively, which all occurred when $R_L = 0.50$.

According to Fig. 1 and the definition of parameter r_{qv}, when best manifold position $R_L \leqslant 0.13$, the emitter flow variation of paired laterals will be equal to that of the single downhill lateral. Under this condition,

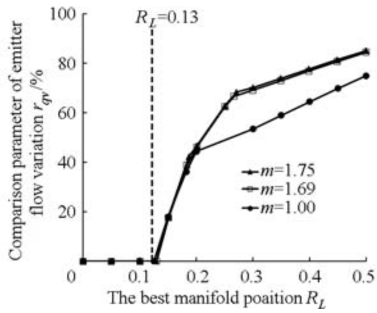


Fig. 1 Relationship between comparison parameter r_{qv} and best manifold position R_L

comparison with the single downhill lateral, the application of the paired layout will increase the investment by the extra materials expenses and illustration cost. On the other hand, when $R_L > 0.13$, the paired layout will decrease the emitter flow variation and increase the water application uniformity. Especially, for the flat ground, it is preferred to use the paired layout.

2.2 Inlet working pressure head

In order to analyze the difference between inlet working pressure head of the paired laterals and single downhill lateral, a parameter r_h was defined as

$$r_h = \left(1 - \frac{h_{0p}}{h_{0s}}\right) \times 100\% \tag{12}$$

Parameter r_h represents the reduced percentage of inlet working pressure head of paired laterals compared with that of the single downhill lateral. Obviously, the greater r_h is, the greater reduced percentage of h_{0p} to h_{0s} is.

Substituting Eq. (2) and Eq. (8) into Eq. (12), and rearranging, r_h could be expressed by

$$r_h = \frac{\left[\frac{m+1}{m+2}(1 - R_L^{m+1}) - \frac{J}{2}(1 + R_L)\right]\frac{\Delta H_F}{h_d}}{1 + \left(\frac{m+1}{m+2} - \frac{1}{2}J\right)\frac{\Delta H_F}{h_d}} \times 100\% \tag{13}$$

Based on Eq. (1), when designing the paired laterals, it should satisfy that

$$\frac{\Delta H_F}{h_d} = \frac{q_{vp}}{x\lambda_p} \cong \frac{h_v}{\lambda_p} \tag{14}$$

where, h_v—emitter pressure head variation

According to Eq. (3), Eq. (5), Eq. (13) and Eq. (14), parameter r_h was only affected by velocity exponent m, emitter pressure head variation h_v, and best manifold position R_L. Fig. 2 showed the relationship between the parameter r_h and best manifold position R_L for velocity exponent m is 1.75, 1.69, 1.00.

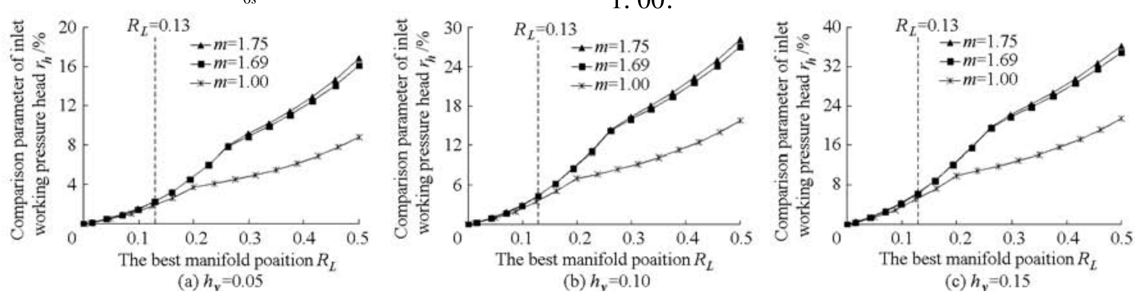


Fig. 2 Relationships between comparison parameter r_h and the best manifold position R_L

From Fig. 2, for the same emitter pressure head variation h_v, parameter r_h increases as the increasing R_L. In Fig. 2a, when best manifold position $R_L \leqslant 0.13$, $r_h < 3\%$, when $R_L = 0.50$, for m is 1.75, 1.69, 1.00, the maximum value of r_h was 16.84%, 16.09% and 8.82%, respectively. In Fig. 2b, when the best manifold position $R_L \leqslant 0.13$, $r_h < 5\%$, when $R_L = 0.50$, for m is 1.75, 1.69 and 1.00, the maximum value of r_h was 28.12%, 27.04% and 15.79%, respectively. In Fig. 2c, when best manifold position $R_L \leqslant 0.13$, $r_h < 7\%$, when $R_L = 0.50$, for m is 1.75, 1.69 and 1.00, the maximum value of r_h was 36.21%, 34.96% and 21.43%, respectively.

According to Fig. 2 and the definition of parameter r_h, when best manifold position $R_L \leqslant 0.13$, the difference between the inlet working pressure head of paired laterals and that of the single downhill lateral was limited. Under this condition, it is prefer to use the single downhill layout. On the other hand, when $R_L > 0.13$, the paired layout will decrease the inlet working pressure head and energy consumption.

Based on the above analysis, considering the irrigation quality, energy consumption and material costs, the paired layout was priority to be applied when best manifold position $R_L > 0.13$. For the condition of $R_L \leqslant 0.13$, it is preferred to use the single downhill layout.

3 Design procedure of micro-irrigation laterals by applying the appropriate layouts

Based on the above analysis, the design procedures for micro-irrigation laterals was revised by using the appropriate layout based on the quantitative criterion. When the diameter D, length L, and other design parameters of the micro-irrigation lateral are given, the design procedure for evaluating emitter flow variation and inlet working pressure head is outlined as follows:

① Calculate parameters h_d, ΔH_S, ΔH_F and J, based on the known parameters.

② When velocity exponent $m = 1.00$, calculate the best manifold position R_L according to parameter J using Eq. (6), when m is 1.69 or 1.75, calculate the best manifold position R_L according to parameter J, using Eq. (5) through the trial-and-error technique or the regression equations from Tab. 2 of Ref. [14].

③ When $R_L > 0.13$, the lateral apply for the paired layout, calculate parameter λ_p according to parameters m, R_L and J, using Eq. (2) or the regression equations from Tab. 2 of Ref. [14]. Calculate parameter q_{vp} and h_{0p}, according to parameters m, J, R_L, λ_p, h_d and ΔH_F, using Eq. (1) and Eq. (2), respectively.

④ When $R_L \leqslant 0.13$, the lateral apply for the single downhill layout, calculate parameter λ_s according to parameters m and J, using Eq. (9). Calculate parameter q_{vs} and h_{0s}, according to parameters m, J, λ_s, h_d and ΔH_F, using Eq. (7) and Eq. (8), respectively.

4 Application and verification

To show the accuracy of the proposed approach, two numerical applications are presented in this section. Tab. 1 shows the know parameters of the design cases. In the design cases, the lateral is polyethylene (PE) pipe, the emitter type is online pressure-compensating emitter, the hydraulic characteristics of the emitters were tested based on Ref. [18], the plant type is vegetable (Case 1) and fruit tree (Case 2).

Based on the design procedure, the design parameters of the micro-irrigation laterals of two cases were calculated. All the design results were shown in Tab. 2.

Tab. 1 Input data for design Cases 1 and 2

Case	D/mm	L/m	s_e/m	F_S	q_d/(L·h^{-1})	k	x	S_0/%
1	14	160	0.5	1.10	2.40	0.70	0.5	5
2	15	100	1.0	1.10	4.00	1.20	0.5	2

Tab. 2 Design results for Cases 1 and 2

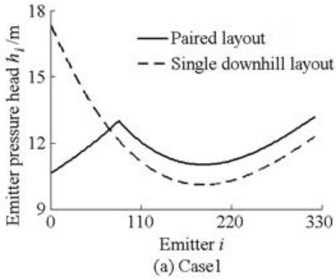
Case	Lateral layout	R_L	q_v	h_0/m
1	Paired	0.257	0.107	13.0
	Single downhill	0	0.286	17.3
2	Paired	0.108	0.033	11.2
	Single downhill	0	0.033	11.5

From Tab. 2, for Case 1, the best manifold position $R_L > 0.13$, emitter flow variation of the paired layout was only 0.107, which satisfy the requirement of GB/T 50485—2009[17]. However, the emitter flow variation of the single downhill layout was greater than 0.20 which couldn't ensure the quality of irrigation. Meanwhile, the inlet working pressure head of the paired layout was 25% less than that of the single downhill layout. Then, even the ground slope $S_0 > 0.03$[1], the lateral of case 1 should still apply for the paired layout.

On the other hand, for Case 2, the best manifold position $R_L < 0.13$, the emitter flow variation of the paired layout was the same to those of the single downhill layout, meanwhile, the difference between the inlet working pressure head of the paired layout and single downhill layout was only 0.3 m. Then, even ground slope $S_0 < 0.03$[1], considering the extra costs from the materials and installations, the lateral of Case 2 was more economically to apply for the single downhill layout.

Base on the design results in Tab. 2 and other known parameters, all the emitter pressure head along the lateral of two cases were calculated by the EGL method, which were shown in Fig. 3.

From Fig. 3a, when the best manifold position $R_L > 0.13$, the paired layout will greatly decrease the pressure head variation and inlet working pressure head than those of the single downhill layout, and then increase the water application uniformity. From Fig. 3b, when the best manifold position $R_L < 0.13$, the emitter pressure heads of the downhill part of the



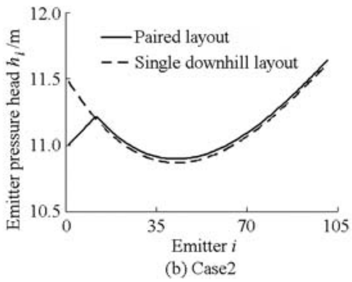


Fig. 3 Pressure head distribution along the micro-irrigation lateral

paired laterals were close to those of the single downhill lateral, the differences of emitter pressure head variation and inlet working pressure head of the two layouts were limited. Combining the results from Tab. 2, it can be proved that the proposed best manifold position $R_L = 0.13$ as the selection criterion of appropriate layout of the micro-irrigation laterals were feasible and reliable.

5 Conclusions

(1) Based on the hydraulic model of micro-irrigation laterals, two parameters r_{qv} and r_h were respectively defined to describe the difference of the emitter flow variation and inlet working pressure head between the paired layout and single downhill layout. By analyzing the effects of two layouts on emitter flow variation and inlet working pressure head, the best manifold position R_L was proposed as the selective parameter. When $R_L > 0.13$, it is preferred to use the paired layout, on the contrast, it is more economical to use the single downhill layout.

(2) The design procedure for the micro-irrigation laterals were revised by applying the appropriate layout. By designing two cases, it can be concluded that comparing with the experience index supposed by Keller, et al[1], the best manifold position criterion was more effective for choosing the appropriate layout. The design procedure were simple and easy to use, which could be directly apply for the micro-irrigation engineering designs.

(3) The proposed criterion of appropriate layout were also suitable for designing the maximum length or the minimum diameter of the micro-irrigation laterals. The criterion of appropriate layout for the tapered laterals needs to be researched further.

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doi:10.6041/j.issn.1000-1298.2016.05.017

均匀坡微灌毛管适宜布置形式优选

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摘要： 根据微灌毛管水力解析模型，通过分析微灌双向布置和单向顺坡布置形式对流量偏差率及毛管进口工作水头的影响，得出均匀坡微灌毛管双向布置的适用条件为最佳支管位置参数大于0.13，当最佳支管位置参数不大于0.13时，微灌毛管宜单向顺坡布置。给出了考虑适宜布置形式的均匀坡微灌毛管设计步骤。通过2个设计实例表明：利用最佳支管位置参数标准可有效选取适宜的毛管布置形式，设计步骤简便可行，可直接应用于微灌工程实践中。

关键词： 微灌；布置形式；双向毛管；解析模型

中图分类号： S275.6　　**文献标识码：** A　　**文章编号：** 1000-1298(2016)05-0123-06

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Key words: micro-irrigation; layout; paired laterals; analytical model

收稿日期：2015-10-17　修回日期：2016-01-06

基金项目： "十二五"农村领域国家科技支撑计划项目(2015BAD22B01-02)、国家国际合作专项(2014DFG72150)和高等学校学科创新引智计划(111计划)项目(B12007)

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引言

管网布置形式是微灌毛管水力设计的前提和基础。大田微灌系统中,常见的微灌毛管布置形式有2种:单向布置和双向布置[1-4]。相比于单向布置,微灌毛管双向布置可以提高灌溉质量,降低系统能耗,但是需要增加一定的投资(材料费和安装费)。目前,针对微灌毛管的水力设计方法已有大量研究:KELLER等[1]基于能坡线法提出了双向微灌毛管最佳支管位置、毛管进口工作压力及灌水器最小工作压力等设计参数的计算公式;蒋树芳等[5]借助于二分法提出了满足允许最大压力水头和最小压力水头,灌水器流量均等的双向微灌毛管设计方法;张国祥[6]基于有限孔数毛管水力学提出了双向毛管布置时的支管位置确定方法,可满足支管两侧毛管灌水器平均流量等于设计流量,同时考虑毛管进口长度比对设计结果的影响;BAIAMONTE等[7-8]提出了双向微灌毛管最佳支管位置、极限管长和最小管径的设计方法;KANG等[9]基于有限元法和黄金分割法,王新坤等[10-13]基于遗传算法分别提出了双向微灌毛管的数值设计方法;JU等[14-15]基于能坡线法,推导了双向微灌同径和异径毛管的最佳支管位置、进口工作压力和灌水均匀度等设计参数的计算公式,进而提出了双向微灌同径和异径毛管极限长度和最小管径的设计步骤。

KELLER等[1]建议微灌毛管双向布置形式仅适用于坡度小于3%的地形条件,但该经验指标缺乏理论依据。国内学者[2-4]建议在地面坡度较小时,宜采用双向布置;当逆坡段毛管长度较短时,应采用单向顺坡布置,但并没有给出定量的指标。因此,有必要对微灌双向毛管的适用条件作进一步分析。

灌水均匀度和毛管进口工作水头分别是灌溉质量和系统能耗的重要指标[1]。本文基于已有的微灌毛管水力解析模型[14,16],通过对比分析微灌双向毛管与单向顺坡毛管的灌水均匀度和进口工作水头,提出均匀坡微灌毛管适宜布置形式的选取标准,在此基础上,提出考虑适宜布置形式的均匀坡微灌毛管设计方法。

1 微灌毛管设计参数解析模型

1.1 双向毛管

双向毛管是指毛管垂直于支管的两侧,水流由支管进入毛管后,向2个相反的方向分流。笔者基于能坡线法提出了仅考虑水力偏差影响的微灌双向毛管流量偏差率 q_{vp} 和进口工作水头 h_{0p}(单位:m)的解析模型[14]分别为

$$q_{vp}=\lambda_p\frac{x\Delta H_F}{h_d}\tag{1}$$

$$h_{0p}=h_d+\left(\frac{m+1}{m+2}R_L^{m+1}+\frac{1}{2}R_LJ\right)\Delta H_F\tag{2}$$

其中

$$\lambda_p=\begin{cases}R_L^{m+1}+R_LJ & (0\leqslant J\leqslant(1-R_L)^m)\\ \dfrac{1}{2c_1}J & \left((1-R_L)^m<J\leqslant\dfrac{m+1}{2^m}\right)\\ c_2J^{c_1} & \left(\dfrac{m+1}{2^m}<J\leqslant2\,\dfrac{m+1}{m+2}\right)\end{cases}\tag{3}$$

$$R_L=\frac{L_{\rm up}}{L}\tag{4}$$

$$\Delta H_F=\frac{F_CF_SKL\,(Nq_d)^m}{D^b}\qquad F_C\cong\frac{1}{m+1}$$

$$q_d=kh_d^x\qquad J=\frac{\Delta H_S}{\Delta H_F}\qquad \Delta H_S=S_0L$$

$$c_1=1+\frac{1}{m}\qquad c_2=\frac{m}{(m+1)^{c_1}}$$

式中 λ_p——双向毛管流量偏差率计算参数
x——灌水器流态指数
ΔH_F——单向顺坡毛管总摩阻损失,m
F_C——克里斯琴森多口系数[17]
F_S——考虑灌水器局部水头损失的毛管总水头损失扩大系数[16],通常取1.10~1.20
K——摩阻系数
N——灌水器总个数
L——毛管长度,m
q_d——灌水器设计流量,L/h
k——灌水器流量系数
D——毛管内径,mm
b——管径指数
h_d——灌水器设计工作水头,m
J——单向顺坡毛管的坡降比
ΔH_S——单向顺坡毛管进口与末端的地形高差,m
S_0——地形坡度,取 $S_0\geqslant0$
c_1、c_2——计算参数
m——流量指数
R_L——双向毛管最佳支管位置设计参数
$L_{\rm up}$——双向毛管逆坡段毛管长度,m

设计参数 m、K 和 b 取值可查阅GB/T 50485—2009《微灌工程设计规范》[17]。

R_L解析模型为[14]

$$(1-R_L)^{m+1}-R_L^{m+1}=\frac{J}{2}\,\frac{m+2}{m+1}\tag{5}$$

当 $m=1$ 时,式(5)可简化为

$$R_L = \frac{1}{2} - \frac{3J}{8} \tag{6}$$

当 $m = 1.69$ 或 $m = 1.75$ 时，式(5)为 R_L 的隐函数，可以在 Excel 中借助“单变量求解”功能，通过迭代法求解，也可通过查阅文献[14]中表 2 回归公式直接计算。

文献[14]中通过 3 个设计实例，表明式(1)和式(2)的计算结果与其他方法的设计结果非常接近，验证了上述双向毛管的水力解析模型的准确性。

1.2　单向顺坡毛管

单向顺坡毛管是指毛管沿垂直于支管方向顺坡铺设。根据能坡线法，借鉴文献[16]，仅考虑水力偏差影响的单向顺坡毛管流量偏差率 q_{vs} 和进口工作水头 h_{0s}(单位：m)的解析模型可分别表示为

$$q_{vs} = \lambda_s \frac{x \Delta H_F}{h_d} \tag{7}$$

$$h_{0s} = h_d + \left(\frac{m+1}{m+2} - \frac{1}{2} J \right) \Delta H_F \tag{8}$$

其中

$$\lambda_s = \begin{cases} 1 - J + c_2 J^{c_1} & (0 \leqslant J < 1) \\ c_2 J^{c_1} & (1 \leqslant J < m+1) \\ J - 1 & (J \geqslant m+1) \end{cases} \tag{9}$$

式中　λ_s——单向顺坡毛管流量偏差率计算参数

2　微灌毛管布置形式对水力设计参数的影响

灌水均匀度和毛管进口工作水头是微灌毛管水力设计的基本参数。通过对比微灌 2 种布置形式对灌水均匀度及毛管进口工作水头的影响，可以从灌水质量及系统能耗角度提出微灌毛管适宜布置形式的选取标准。

2.1　灌水均匀度

为了对比分析双向毛管流量偏差率 q_{vp} 与单向顺坡毛管流量偏差率 q_{vs} 间的差异，定义参数 r_{qv} 为

$$r_{qv} = \left(1 - \frac{q_{vp}}{q_{vs}} \right) \times 100\% \tag{10}$$

参数 r_{qv} 表征了双向毛管流量偏差率 q_{vp} 相比单向顺坡毛管流量偏差率 q_{vs} 减少的百分比。显然，r_{qv} 越大，表示 q_{vp} 比 q_{vs} 减少得越多，反之亦然。

将式(1)、(7)代入式(10)整理得到

$$r_{qv} = \left(1 - \frac{\lambda_p}{\lambda_s} \right) \times 100\% \tag{11}$$

根据式(3)、(9)、(11)，绘制了不同流量指数 m 对应的流量偏差率对比参数 r_{qv} 与最佳支管位置参数 R_L 的关系，如图 1 所示。

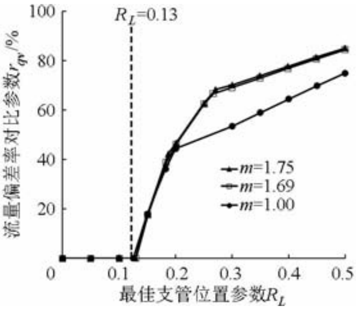

图 1　流量偏差率对比参数 r_{qv} 与最佳支管位置参数 R_L 的关系

Fig. 1　Relationship between comparison parameter r_{qv} and the best manifold position R_L

从图 1 可以看出，当 $R_L \leqslant 0.13$ 时，$r_{qv} = 0$；当 $R_L > 0.13$ 时，$r_{qv} > 0$，且 r_{qv} 随 R_L 增大而增大；当 $R_L = 0.50$ 时，r_{qv} 达到最大值，分别为 85.13%($m = 1.75$)、84.50%($m = 1.69$)和 75%($m = 1.00$)。

根据图 1 结果，结合流量偏差率对比参数 r_{qv} 的定义，当最佳支管位置参数 $R_L \leqslant 0.13$ 时，微灌双向毛管与单向顺坡毛管的流量偏差率相等，若双向布置微灌毛管，反而会因为额外的安装费和材料费而增加系统投资；当 $0.13 < R_L \leqslant 0.50$ 时，微灌毛管双向布置相比单向顺坡布置可以降低流量偏差率，从而提高灌水均匀度，尤其是平坡地形，应优先采用微灌双向毛管。

2.2　毛管进口工作水头

为了对比分析双向毛管进口工作水头 h_{0p} 与单向顺坡毛管进口工作水头 h_{0s} 间的差异，定义参数

$$r_h = \left(1 - \frac{h_{0p}}{h_{0s}} \right) \times 100\% \tag{12}$$

参数 r_h 表征了双向毛管进口工作水头 h_{0p} 相比单向顺坡毛管进口工作水头 h_{0s} 减少的百分比。显然，r_h 越大，表示 h_{0p} 比 h_{0s} 减少得越多，反之亦然。

将式(2)、(8)代入式(12)，并整理得

$$r_h = \frac{\left[\frac{m+1}{m+2}(1 - R_L^{m+1}) - \frac{J}{2}(1 + R_L) \right] \frac{\Delta H_F}{h_d}}{1 + \left(\frac{m+1}{m+2} - \frac{1}{2} J \right) \frac{\Delta H_F}{h_d}} \times 100\% \tag{13}$$

根据式(1)，设计微灌双向毛管时，满足条件

$$\frac{\Delta H_F}{h_d} = \frac{q_{vp}}{x \lambda_p} \cong \frac{h_v}{\lambda_p} \tag{14}$$

式中　h_v——压力偏差率

将式(14)代入式(13)中，同时，根据式(3)、(5)，毛管进口工作水头对比参数 r_h 仅与流量指数 m、压力偏差率 h_v 及最佳支管位置参数 R_L 相关。图 2 分别绘制了不同压力偏差率时，不同流量指数 m 对应的毛管进口工作水头对比参数 r_h 与最佳支管位置参数 R_L 的关系。

从图 2 可以看出，当压力偏差率 h_v 相同时，r_h 随 R_L 增大而增大；当 R_L 相同时，r_h 随 h_v 增大而增大。

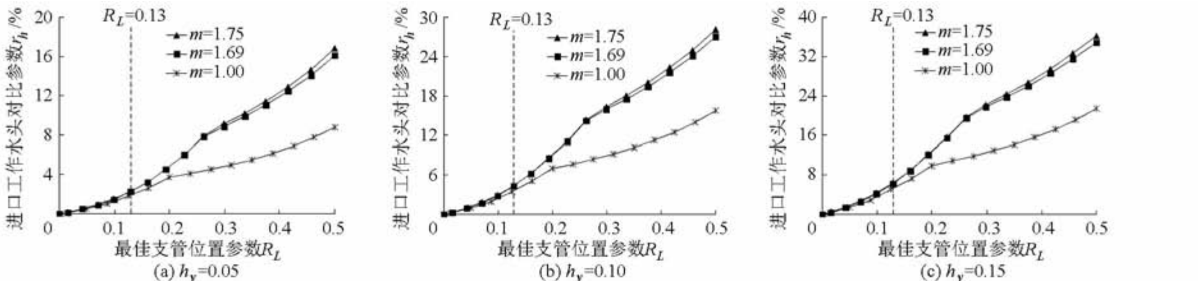

图 2 毛管进口工作水头对比参数 r_h 与最佳支管位置参数 R_L 的关系

Fig. 2 Relationship between comparison parameter r_h and the best manifold position parameter R_L

图 2a 中，当 $R_L \leqslant 0.13$ 时，$r_h < 3\%$；当 $R_L = 0.50$ 时，r_h 分别为 16.84%（$m = 1.75$）、16.09%（$m = 1.69$）和 8.82%（$m = 1.00$）。图 2b 中，当 $R_L \leqslant 0.13$ 时，$r_h < 5\%$；当 $R_L = 0.50$ 时，r_h 分别为 28.12%（$m = 1.75$）、27.04%（$m = 1.69$）和 15.79%（$m = 1.00$）。图 2c 中，当 $R_L \leqslant 0.13$ 时，$r_h < 7\%$；当 $R_L = 0.50$ 时，r_h 分别为 36.21%（$m = 1.75$）、34.96%（$m = 1.69$）和 21.43%（$m = 1.00$）。

根据图 2 结果，结合毛管进口工作水头对比参数 r_h 的定义，当最佳支管位置参数 $R_L < 0.13$ 时，微灌毛管双向布置相比单向顺坡布置的进口工作压力相差不大，此时毛管宜采用单向顺坡布置形式；当 $0.13 < R_L \leqslant 0.50$ 时，微灌毛管双向布置相比单向顺坡布置可以减少进口工作压力，从而降低系统能耗。

因此，综合考虑灌水质量、系统能耗及管网成本，均匀坡微灌毛管双向布置的适用条件为最佳支管位置参数 $R_L \geqslant 0.13$；当 $R_L < 0.13$ 时，微灌毛管宜采用单向顺坡布置形式。

3 考虑适宜管网布置形式的微灌毛管设计步骤

现有的微灌毛管设计方法中，由于缺少相关量化指标，无法选取适宜的毛管布置形式。基于上述研究结果，在已知微灌毛管管径、管长及其他设计变量的条件下，评价灌水均匀度，同时确定毛管进口工作水头的设计步骤为：

（1）根据已知参数，分别计算参数 h_d、ΔH_S、ΔH_F 和 J。

（2）当 $m = 1$ 时，根据 J 的值，利用式（6）计算参数 R_L；当 $m = 1.69$ 或 $m = 1.75$ 时，可根据 J 的值，利用式（5）通过迭代法或利用文献[14]中表 2 的回归公式计算 R_L。

（3）当 $R_L > 0.13$ 时，微灌毛管双向布置，根据 m、R_L 和 J 的值，利用式（3）或文献[14]中表 2 的回归公式计算参数 λ_p；根据 m、J、λ_p、h_d 和 ΔH_F 的值，分别利用式（1）和式（2）计算双向毛管流量偏差率 q_{vp} 和进口工作水头 h_{0p}。

（4）当 $R_L \leqslant 0.13$ 时，微灌毛管单向顺坡布置，根据 m 和 J 的值，利用式（9）计算参数 λ_s；根据 m、J、λ_s、h_d 和 ΔH_F 的值，分别利用式（7）和式（8）计算单向顺坡毛管流量偏差率 q_{vs} 和进口工作水头 h_{0s}。

4 案例验证

通过 2 个设计实例验证以上研究结果及设计步骤的可靠性。表 1 分别给出了各设计实例的已知参数。设计实例中，毛管为聚乙烯（PE）管材，灌水器类型为管上式压力补偿滴头，滴头水力性能根据文献[18]测定，作物类型分别为蔬菜（实例 1）和果树（实例 2）。

表 1 实例 1、2 的已知参数

Tab. 1 Input data for design case 1 and case 2

实例	毛管管径 D/mm	毛管管长 L/m	滴头间距 s_e/m	局部水头损失扩大系数 F_S	滴头设计流量 q_d/(L·h^{-1})	流量系数 k	流态指数 x	地形坡度 S_0/%
1	14	160	0.5	1.10	2.40	0.70	0.5	5
2	15	100	1.0	1.10	4.00	1.10	0.5	2

根据上述设计步骤，分别计算了 2 个实例中毛管采用单向顺坡布置及双向布置的设计参数，结果见表 2。

从表 2 中可以看出，实例 1 中最佳支管位置参数 $R_L > 0.13$，计算得双向毛管的流量偏差率仅为 0.107，满足《微灌工程设计规范》对灌水均匀度的要求，而单向顺坡毛管的流量偏差率则大于 0.20，不能保证灌溉质量，同时双向毛管相比单向顺坡毛管的进口工作水头降低约 25%。因此，虽然地形坡度大于 KELLER 等[1]推荐的 3%，但实例 1 中的微灌毛管仍需要选用双向布置形式。另一方面，实例 2 中最佳支管位置参数 $R_L < 0.13$，双向毛管与单向

表 2　实例 1、2 的设计结果

Tab. 2　Design results for design case 1 and case 2

实例	布置形式	最佳支管位置参数 R_L	流量偏差率 q_v	毛管进口工作水头 h_0/m
1	双向	0.257	0.107	13.0
	单向顺坡	0	0.286	17.3
2	双向	0.108	0.033	11.2
	单向顺坡	0	0.033	11.5

顺坡毛管的流量偏差率相同，且毛管进口工作压力仅减少 0.3 m。虽然地形坡度小于 KELLER 等[1]推荐的 3%，但考虑到毛管双向布置需要增加材料费及安装费，实例 2 中的微灌毛管宜采用单向顺坡布置形式。

根据表 2 中的设计结果及已知参数，基于能坡线法分别计算了实例 1 和实例 2 中 2 种布置形式的毛管上各灌水器工作水头，如图 3 所示。

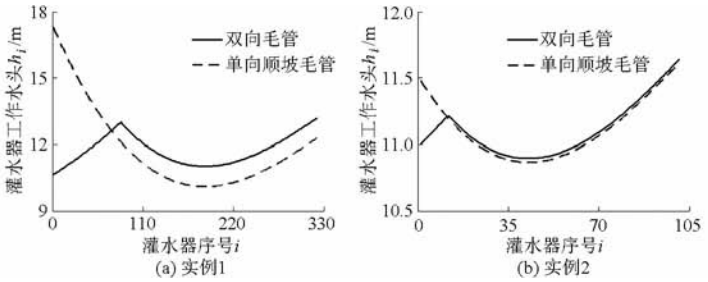

图 3　各设计实例中微灌毛管上灌水器工作水头分布

Fig. 3　Pressure head distribution along the micro-irrigation lateral

从图 3a 可以看出，当双向毛管逆坡段管长较长时（$R_L>0.13$），相比单向顺坡毛管，双向布置毛管可以显著减少压力偏差，从而提高灌水均匀度，同时降低毛管进口工作水头；从图 3b 可以看出，当双向毛管逆坡段管长较短时（$R_L\leqslant 0.13$），双向布置毛管的顺坡段毛管上灌水器工作水头分布与单向顺坡毛管几乎完全一致，其压力偏差率相等，且进口工作压力差异很小。结合表 2 的设计结果证明：本研究提出的以最佳支管位置参数 R_L 为依据选取微灌毛管适宜布置形式是可行的。

5　结论

（1）基于微灌毛管水力解析模型，分别定义了流量偏差率对比参数 r_{qv} 及毛管进口工作水头对比参数 r_h，通过分析微灌双向布置和单向顺坡布置形式对流量偏差率及毛管进口工作水头的影响，得出均匀坡微灌毛管双向布置的适用条件为最佳支管位置参数 $R_L>0.13$；当 $R_L\leqslant 0.13$ 时，微灌毛管宜单向顺坡布置。

（2）提出了考虑适宜布置形式的均匀坡微灌毛管设计步骤，并通过 2 个设计实例进行验证，结果显示：相比于 KELLER 等[1]提出的地形坡度经验值，本文提出的最佳支管位置参数 R_L 设计标准可以有效地确定微灌毛管的适宜布置形式，设计步骤简单高效，可直接应用于微灌工程实践中。

（3）提出的微灌毛管适宜布置形式的选取标准同样适用于已知灌水均匀度和相关参数，设计毛管最小管径或极限管长等情况。本文中微灌毛管为同径管，对异径毛管适宜布置形式的选取标准还有待进一步研究。

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