HYDRAULIC CHARACTERISTICS AND COMPUTERIZED DESIGN OF MICROIRRIGATION SYSTEMS

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Abstract
Hydraulic characteristics of microirrigation laterals and submain units are as follows:
(1) Water application uniformity of a lateral is affected by the lateral diameter, lateral length and field slopes. In uphill and zero slopes, water application uniformity increases as lateral diameter increases or length decreases. However, it may decrease as lateral diameter increases or lateral length decreases in downhill slope conditions sometimes.
(2) Water application uniformity of a submain unit is affected by lateral diameter, lateral length, submain diameter, submain length and field slopes. Water application uniformity may increase as diameters of laterals and submain increase or lengths of laterals and submain decrease in some conditions. Sometimes, it may decreases as diameters of laterals and submain increase or lengths of laterals and submain decrease.
(3) Lateral diameter and length, and submain diameter and length have multiple solutions when required average emitter discharge and water application uniformity are satisfied. Series computerized methods have been developed for hydraulic design of microirrigation laterals and submain units to satisfy required average emitter discharge and water application uniformity using the finite element method and the method using the lateral discharge equation, back step method and forward step method. Microirrigation laterals and submain units at any field conditions can be designed easily, accurately and quickly with these methods using personal computers.

Keywords agriculture, computerized design, hydraulic characteristics, microirrigation, operation pressure, water application, water application uniformity
1. INTRODUCTION

The hydraulic characteristics and design methods of laterals and submain units are very important. This is because the laterals are relatively independent in hydraulics when pressure regulators or micro tubing are installed at the inlets of laterals in microirrigation systems and the laterals should be considered as whole systems in hydraulic design. The submain units are relatively independent in hydraulics when pressure regulators are only installed at the inlets of submain units and the submain units should be considered as whole systems in hydraulic design.

Required average emitter discharge and water application uniformity are two very important parameters. Required average emitter discharge, which is determined using the field experiment or mathematical calculation according to the soil physical characteristics and crop root distribution, ensures the irrigation water to be just applied to the crop root zones. Required water application uniformity ensures every crop getting the desired minimum quantity of irrigation water.

Earlier hydraulic design methods (Myers and Bucks, 1972; Wu and Gitlin, 1973) were aimed at designing trickle laterals where submains are considered to have a similar hydraulic characteristic to the laterals. These methods were developed using Bernoulli energy equation and Darcy-Weisbach equation where the emitter discharges per unit lateral lengths are assumed to be the same along a lateral. In these methods, the actual emitter distribution (scattered distribution) is considered.

After the above methods, some methods (Howell and Hiler, 1974a and 1974b; Keller and Karmeli, 1974; Wu and Gitlin, 1974a and 1974b) were developed for lateral design by assuming the emitters distribute continuously and the emitter discharges per unit lateral lengths are the same along laterals. The total pressure head loss along a lateral due to friction is determined using the integral technique. Further, mathematical equations (Wu and Gitlin, 1974b and 1975a) were developed to express the pressure distribution along a lateral named energy gradient lines. Using the equations and theories for energy gradient lines, many methods (Gillespie et al., 1979; Keller and Bliesner, 1990; Wu, 1985, 1991, 1992a and 1992b; Wu and Gitlin, 1977a and 1977b) were developed for design of microirrigation laterals and submains on zero, uniformly and nonuniformly sloping fields. In these methods, the submain
unit is divided into lateral and submain in hydraulic design when the above methods are used
whatever the pressure regulators or micro tubing are installed at lateral inlets or not. The
lateral is designed based on the given conditions first. The submain is then designed by
considering a range of pressure variation, which can approximately create the desired water
application uniformity and average emitter discharge in submain units. The emission
exponent is not considered in all the energy gradient equations.

Warrick and Yitayew presented an alternative treatment for microirrigation lateral design
(Warrick and Yitayew, 1988) where the emitters are considered to be close enough that the
lateral can be regarded as a homogeneous system of a main tube and a longitudinal slot. This
treatment includes a spatially variable discharge function. It dismissed the assumption of
equal emitter discharge along the lateral, as suggested in the above methods. In addition,
Yitayew and Warrick presented a chart to design laterals (Yitayew and Warrick, 1988). When
the required average emitter discharge, the required water application uniformity, and other
conditions are given, lateral length or diameter with operating pressure head can be
determined.

Hathoot et al. presented a stepwise computer calculation method for analysis and design of
laterals (Hathoot et al., 1993). In their method, a small increment of pressure head is given at
the inlet of the lateral. A design chart similar to that presented by Yitayew and Warrick
(Yitayew and Warrick, 1988) is developed.

An important component of designing paired laterals is to determine the best submain
position. Keller and Bliesner (1990) reported that the best submain position is that location
where the same minimum pressure exists in uphill and downhill laterals. This concept is very
useful when the methods presented by Keller and Bliesner (Keller and Bliesner, 1990), and
Wu and Gitlin (Wu and Gitlin, 1975) are used. However, it was found that this location is the
approximate solution of the best submain position in most cases when considering
Christiansen's uniformity coefficient (UCC), lower-quarter distribution uniformity (DU) and
emitter flow variation (VHM).

The finite element method was presented to analyze the hydraulics of submain units (Bralts
and Segerlind, 1985) first. Then, it is applied on the hydraulic analysis of pipe networks
(Haghighi et al., 1988; Haghighi et al., 1989; Mohtar et al., 1991), the hydraulic analysis of
sprinkle irrigation systems (Saldivia et al., 1990), and the hydraulic analysis of microirrigation systems (Bralts et al., 1993; Kang and Nishiyama, 1994). The advantages are: (1) submain units are considered as whole systems; (2) actual emitter distribution is considered; (3) emission coefficient and exponent are considered; (4) pressure head and discharge of every emitter are determined; and (5) calculation accuracy is very high.

From 1994, Kang and Nishiyama developed a new finite element model using a lateral discharge equation (Kang et al. 1995; Kang and Nishiyama, 1996a). Then, Kang et al. developed a series of methods for design microirrigation laterals and submain units according to the average emitter discharge and water application uniformity using this new finite element analytical procedure (Kang and Nishiyama, 1996b, 1996c and 1997; Kang et al., 1996; Kang et al., 1999). Kang et al. also developed a series of methods for design microirrigation laterals and submain units according to the average emitter discharge and water application uniformity using the lateral discharge equation, golden section search, back step method and forward step method (Kang and Nishiyama, 1995, 1996d and 1996e; Kang et al., 1998).

During the above research, the hydraulic characteristics of microirrigation laterals and submain units have been studied more clearly. This paper is a summary of the research results on hydraulic characteristics of microirrigation systems and design methods for laterals and submain units found by the author with his co-workers.

2. HYDRAULIC CHARACTERISTICS

2.1 Hydraulic Characteristics of Laterals

Fig. 1 shows the relationship of water application uniformity (Christiansen's uniformity coefficient, UCC) to lateral diameter when the operating pressure heads of laterals produce required average emitter discharge ($q_{req}$), and the lateral lengths are given.
The relationship between UCC and lateral diameter has two shapes (Shapes I and II) when the minimum diameter for the lateral is small enough, and the maximum diameter for the lateral is large enough. The curve of UCC versus lateral diameter appears as Shape I when: (1) single laterals are on uniformly uphill and zero sloping fields; (2) single laterals are on the nonuniformly sloping fields where general slopes tend to uphill; (3) paired laterals are on the zero sloping fields; and (4) paired laterals are on the nonuniformly sloping fields where general slopes tend to zero. The lateral diameter has unique solution if UCC equals to required water application uniformity (required Christiansen's uniformity coefficient, UCC_{req}). The lateral diameters which are equal to or more than this solution are acceptable because UCC for these diameters are higher than UCC_{req}. The curve of UCC versus lateral diameter
appears as Shape II when: (1) single laterals are on uniformly downhill sloping fields; (2) single laterals are on the nonuniformly sloping fields where general slopes tend to downhill; (3) paired laterals are on sloping fields; and (4) paired laterals are on the nonuniformly sloping fields where general slopes will not tend to zero. The lateral diameter may have one solution or two solutions if UCC equals to UCC\textsubscript{req}. If there are two solutions, the lateral diameters within the region of these two solutions are acceptable. If there is only one solution, there may be two cases. First case, UCC at top point on the curve of UCC versus lateral diameter equal UCC\textsubscript{req}. In this case, only the diameter on this point is acceptable. Second case, UCC at all the points in the right hand side of this solution on the curve are higher than UCC\textsubscript{req}. Thus, all the lateral diameters in the right hand side of this solution (including this solution) are acceptable.

Fig. 2 shows the relationship of UCC to lateral length when the operating pressure heads of laterals produce q\textsubscript{req} and the lateral diameters are given. The curves for the relationship of UCC to lateral length has three shapes (Shapes I, II and III) when the minimum length for the lateral is small enough, and the maximum length for the lateral is large enough. The curve of UCC versus lateral length appears as Shape I when single laterals are on uniformly uphill and zero sloping fields, and paired laterals are on the zero sloping fields. The lateral length has unique solution if UCC equals to UCC\textsubscript{req}. The lateral length which are equal to or less than this solution are acceptable because UCC for these diameters are higher than UCC\textsubscript{req}. The curve of UCC versus lateral length appears as Shape II when a single lateral is on a uniformly downhill sloping field, or paired laterals are on uniformly sloping fields. The lateral length may have one solution, two solutions or three solutions if UCC equals to UCC\textsubscript{req}. If there is only one solution, all the lateral length that are equal to or less than this solution are acceptable. If there are two solutions, all the lateral lengths (including these two solutions) excepting those within the range of these two solutions are acceptable. If there are three solutions, all the lateral lengths (including the three solutions) excepting those within the range of the smallest solution and middle solution and in the right hand side of the biggest solution are acceptable. The curve of UCC versus lateral length appears as Shape III when single laterals and paired laterals are on nonuniformly sloping fields. The lateral length may have multiple solutions if UCC equals UCC\textsubscript{req}. The suitable length of laterals can then be determined by analyzing the curve of UCC versus lateral length.
Fig. 2. Relationship of water application uniformity UCC to lateral length.
Fig. 3. Relationship of UCC to lateral and submain diameters for a submain unit with single laterals in a zero sloping field.

Fig. 4. Relationship of UCC to lateral and submain diameters for a submain unit with single laterals in a downhill sloping field.

2.1 Hydraulic Characteristics of Submain Units

Generally, there are four cases in design of microirrigation submain units: (1) to find the diameters of the lateral and submain, the best submain position (paired laterals) and operating pressure head of the submain unit according to $q_{req}$ and required water application uniformity.
when the lengths of laterals and submain are given; (2) to find lateral length and submain diameter, the best submain position (paired laterals) and operating pressure head of the submain unit according to $q_{req}$ and required water application uniformity when the lateral diameter and submain length are given; (3) to find the lengths of the lateral and submain, the best submain position (paired laterals) and operating pressure head of the submain unit according to $q_{req}$ and required water application uniformity when the diameters of laterals and submain are given; and (4) to find lateral diameter and submain length, the best submain position (paired laterals) and operating pressure head of the submain unit according to $q_{req}$ and required water application uniformity when the lateral length and submain diameter are given.

Research result shows that water application uniformity is cooperatively affected with lateral diameter, lateral length, submain diameter and length in a submain unit. In traditional opinion, water application uniformity increases as lateral diameter increases for a submain unit with single laterals in a zero sloping field. However, it is found that UCC increases as lateral diameter increases in first stage for a submain diameter, and then UCC decreases as lateral diameter increases after (Fig. 3). The change rule of UCC affected with lateral diameter, lateral length, submain diameter and length are similar to that in zero sloping fields if there is a uphill slope along laterals. In case there is a downhill slope along laterals, UCC also increases as lateral diameter increases in first stage for a submain diameter, and then UCC decreases as lateral diameter increases. But it is different with the relationships of UCC to lateral and submain diameters on zero slopes as shown by Fig. 4.

In research work, it is found that the lateral diameter, which can create the $UCC_{req}$ and $q_{req}$, decreases as field slope increases when the laterals toward downhill slopes. In a design example, it was found that UCC of a submain unit reaches to 0.90 in a field with downhill slopes of 30° when the lateral diameter is equal to 9 mm.

When the submain is arranged toward downhill slopes, the change rule of UCC to submain and lateral parameters is similar to that when laterals are arranged toward the downhill slopes. However, the system cost will be less when laterals arranged toward slopes because there are many laterals in a submain unit.

The research results for Cases 2, 3 and 4 also show that water application uniformity is cooperatively affected by the lateral and submain parameters.
The above results were obtained when a submain unit is considered as a whole system, and
the finite element methods (Kang et al. 1995; Kang and Nishiyama, 1996a, 1996b, 1996c and
1997, Kang et al., 1996; Kang et al. 1999) or the methods developed using the lateral
discharge equation, golden section search, back step method and forward step method (Kang
and Nishiyama, 1995, 1996d and 1996e; Kang et al., 1998) are used. If using the traditional
methods, the above results can not be found because a submain unit is divided into lateral and
submain separated in hydraulic design, and water application uniformity can not be evaluated
accurately in the submain unit.

When design a submain unit with paired laterals, the best submain position should be
determined first. In traditional methods for designing submain units with paired laterals, only
the lateral parameters (length and diameter) and the field slope along the lateral are
considered. The best submain position is considered to be located at the center of a lateral in
zero sloping fields. However, it is found that the best submain position of paired laterals is
also affected by the submain parameters (length and diameter) and the field slope along a
submain when the submain is considered as a whole systems.

3. COMPUTERIZED METHODS FOR DESIGNING MICROIRRIGATION
SYSTEMS

3.1 The Design Methods for Laterals

The methods with computer programs using the finite element method (Kang et al. 1995;
Kang and Nishiyama, 1996a) and using the lateral discharge equation, golden section search,
back step method and forward step method (Kang and Nishiyama, 1995) have been developed
(Kang and Nishiyama, 1996b, 1996d; Kang et al., 1996; Kang et al., 1998; Kang et al. 1999)
for design of microirrigation laterals. When a parameter of lateral diameter or length is given,
another parameter, the best submain position (paired laterals) and operating pressure head at
minimum cost (system cost and operating cost) at any field condition can be accurately
designed using a personal computer. When a lateral is designed to produce $q_{\text{req}}$ and $\text{UCC}_{\text{req}}$,
the general procedures of the above methods are:
Step 1: Choose a series of values for the design parameter from smallest to largest (uniform slopes) or from largest to smallest (nonuniform slopes).

Step 2: Find required operating pressure head ($H_{in}$) that can create $q_{req}$, the best submain position (paired laterals) and to evaluate the water application uniformity for each given value.

Step 3: Determine the design parameter from the relationship of water application uniformity to the design parameter according to the required water application uniformity.

Step 4: Determine the best submain position from the relationship of the best submain position to the design parameter according to the design parameter determined in Step 3.

Step 5: Determine the operating pressure head from the relationship of the operating pressure head to the design parameter according to the design parameter determined in Step 3.

In the above procedure, Step 2 is implemented using two methods. In first method (Kang and Nishiyama, 1996b; Kang et al., 1996; Kang et al. 1999), the finite element method is used for hydraulic calculation. The golden section search is used for searching the operating pressure head that can create the $q_{req}$. For searching the best submain position, the author with his co-workers also developed methods for designing laterals on uniform slopes and nonuniform slopes. The methods will not be mentioned here due to the limitation of paper length. In second method (Kang and Nishiyama, 1996d; Kang et al., 1998), the lateral discharge equation, back step method and forward step method are used for hydraulic calculation. A method is developed for searching the operating pressure head that can create the $q_{req}$. The method for searching the best submain position is the same as in the first method. Also, the methods will not be mentioned here due to the limitation of paper length.

If one considers the optimization of the sum of system cost and operating cost, the ranges of the design parameter that can satisfy the condition of UCC being more than or equal to $UCC_{req}$ can be found from the relationship of water application uniformity to the design parameter in Step 3 of the above procedure. Then, the values for design parameter in these ranges can be found according to the material information in the markets. After the corresponding best submain positions and operating pressure heads for the design parameters determined from the relationships of the best submain position to the design parameter and the operating pressure head to the design parameter according to the design parameter
determined in Step 3, the system cost and operating cost for each design parameter can be calculated, and the design parameter with the minimum sum of system cost and operating cost can then be determined. Fig. 5 shows the relationships of design parameter to UCC, the best submain position and operating pressure head of a design example for diameter of paired laterals on nonuniform slopes. When UCC = UCC\text{req} = 0.96, the lateral diameter is 14.9 mm, the best submain position is located at the center of the laterals, and operating pressure head is 6.11 m. If one consider UCC being more than or equal to UCC\text{req}, all the lateral diameters in the range from 14.9 mm to 21.0 mm are acceptable.

3.2 The Design Methods for Submain Units

If assume that LD_1, LD_2, LD_3, …, LD_N is a group of lateral diameters from smallest to largest in a same increment, SD_1, SD_2, SD_3, …, SD_N is a group of submain diameters from smallest to largest in a same increment, LL_1, LL_2, LL_3, …, LL_N is a group of lateral lengths from smallest to largest in a same increment, SL_1, SL_2, SL_3, …, SL_N is a group of submain lengths from smallest to largest in a same increment, there would be n \times n combinations for each design case. After the water application uniformity, the best submain position (submain units with paired laterals) and operating pressure head that make the submain unit satisfying q_{req} is determined using the finite element method (Kang et al 1995; Kang and Nishiyama, 1996a, 1996c and 1997) for each combination of a design case, the isoline maps for the relationships of water application uniformity to the design parameters of submain and lateral, the best position (submain units with paired laterals) to the design parameters of submain and lateral and the operating pressure head to the design parameters of submain and laterals can be plotted. The regions where water application uniformity is more than or equal to required water application uniformity are found from the isoline maps. The combinations of the design parameter are determined from the isoline map for the relationship of water application uniformity to the design parameters of the submain units according to the material information in the markets. The best submain positions (submain unit with paired laterals) for these combinations are determined from the isoline map for the relationship of the best submain position to the design parameters of the submain units. The operating pressure head for these combinations are determined from the isoline map for the relationship of the operating pressure head to the design parameters of the submain units. After the system costs and operating costs for the combinations calculated, the combination with minimum cost of
material and operation (energy cost) is easily found by comparison.

Fig. 5. Relationships of the diameter of paired laterals to UCC, the best submain position and operating pressure head on a nonuniform sloping field.
Fig. 6. Relationship of UCC to the diameters of submain and lateral of a submain unit with paired laterals.
Fig. 7. Relationship of the pest submain position to the diameters of submain and lateral of the submain unit with paired laterals.

Fig. 8. Relationship of the operating pressure head to the diameters of submain and lateral of the submain unit with paired laterals.
Using the above methods, any submain unit at any field conditions (uniform sloping fields, nonuniform sloping fields, regular field and irregular fields) can be easily designed in high accuracy using personal computers by considering the submain units to be whole systems.

Figs. 6, 7 and 8 show the isoline maps for the relationships of UCC to the diameters of lateral and submain, the best submain position to the diameters of lateral and submain and the operating pressure head to the diameters of laterals and submains for a design example with paired laterals. If UCC \( \text{req} \) is 0.96, and the materials for laterals and submains in markets are: 10 mm, 12 mm, 15 mm, 16 mm, 18 mm, 20 mm, 25 mm, 32 mm, 40 mm, 50 mm, 60 mm, 65 mm, 70 mm, 80 mm and 100 mm. It can be found that the suitable combinations of lateral diameter and submain diameter are: 15 mm (lateral diameter) - 65 mm (submain diameter), 15 mm - 70 mm, 15 mm - 80 mm, 16 mm - 65 mm, 16 mm - 70 mm, 16 mm - 80 mm, 18 mm - 65 mm, 18 mm - 70 mm, 18 mm - 80 mm and 20 mm - 80 mm according to the principle of UCC being more than or equal to 0.96. If only the material cost is considered, the combination 15 mm - 65 mm is good, the corresponding best submain position and operating pressure head are 42.5 m (counted from the upper end of the paired laterals) and 19.54 m, respectively. UCC for this combination is 0.967.

4. CONCLUSION

In this paper, the author summarized the new findings of hydraulic characteristics of microirrigation laterals and submain units and the computerized methods for hydraulic design of laterals and submain units. These hydraulic characteristics are:

(1) Water application uniformity of a lateral is affected by the lateral diameter, lateral length and field slopes. In uphill and zero slopes, water application uniformity increases as lateral diameter increases or length decreases. However, it may decrease as lateral diameter increases or lateral length decreases in downhill slope conditions sometimes.

(2) Water application uniformity of a submain unit is affected by lateral diameter, lateral length, submain diameter, submain length and field slopes. Water application uniformity may increase as diameters of laterals and submain increase or lengths of laterals and submain decrease in some conditions. Sometimes, it may decreases as diameters of laterals and submain increase or lengths of laterals and submain decrease.

(3) Lateral diameter and length, and submain diameter and length have multiple solutions.
when required average emitter discharge and water application uniformity are satisfied. Series computerized methods have been developed for hydraulic design of microirrigation laterals and submain units to satisfy required average emitter discharge and water application uniformity using the finite element method and the method using the lateral discharge equation, back step method and forward step method. Microirrigation laterals and submain units at any field conditions can be designed easily, accurately and quickly with these methods using personal computers.

The details of the contents can be found in the publications by the author with his copartners. The corresponding computer programs will be published as software soon.

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