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Optimal design of pressurized irrigation laterals installed on sloping land

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ABSTRACT: A new and relatively precise method was developed for correct design of pressurized irrigation laterals installed on sloping land with constant diameter. This method is combination of analytical and optimization methods. By the method minimum and maximum pressure and range of its variations can be calculated. On base of this calculations optimal length of lateral is determined, so that the range of pressure variations is not more than its allowable value. Results of this paper were presented as a table in order to guide line of design. It showed that two types of pressure distributions for laterals installed on sloping land. The first type occur when the pressure is decreasing and then increasing and thus there is a point for relative minimum pressure on lateral. In this distribution, difference between elevations of two ends of lateral to energy loss ratio is less than 2.852. If this ratio be more than 2.852, the second type distribution. In this distribution the pressure is increasing and reaches to its maximum value at end of lateral.
Keywods: lateral, pressurized irrigation, optimization, design , distribution , analytical

INTRODUCTION

Laterals are penstocks including some outflows as sprinklers or drains. Various methods are used for designing such laterals in most of which attempt has been made to consider pressure distribution and discharge alongside the lateral. In laterals placed on steep surfaces, two factors of energy fall and height difference at the two lateral head are involved in the form of pressure distribution such that, through changing the ration between the above factors, the distribution form changes as well. Therefore in the methods used for designing the laterals, such factors should be considered. As a whole, these methods can be divided into three groups: the first group includes the analytic methods like the method proposed by Valiantaze in 1998 (1) which are based on the line slope analysis along the lateral. The second group concern the numerical methods like the numerical method of finite components proposed by Braltz and Segerlind in 1985 (2) and Braltz et al. in 1993 (3). The third group includes the optimization methods.

In these methods it has been attempted to eliminate expenses or pressure difference alongside the lateral. For example Pleaban et al. in 1984 (4) and Saad and Marino in 2002 (5) proposed an optimization method for minimizing the expense of Laterals with different diameters. Also, Valiantaze in 2002 (6) suggested this method for minimizing the pressure difference along the laterals with different diameters. He assumed the energy line slope to be constant.

In this paper a simple and partially precise method will be proposed for designing laterals with constant diameter and established in sloped areas. This is a combination of analytic and optimization methods. First the minimum and maximum pressure in the lateral will be computed via an analytic method. In this section the hypothesis of constancy of energy line slope proposed by Valiantase will not be observed which will lead to increased precision of the method(7). Then, through an optimization method, the lateral's length is such computed that the pressure difference between the minimum and maximum pressures minimizes.

MATERIALS AND METHODS

Pressure distribution along a lateral established on a steep surface with constant diameter is as follows:
If the flow rate along a lateral is assumed to be linear then the following equation holds:

$$Q(x) = Q\,x'/L \quad (1)$$

$$x' = L - x \quad (2)$$

That in the above relations, the referral flow rate at the distance x from its origin = Q(x), Q= flow rate of the beginning of the lateral and L=length of the lateral.
The amount of energy dissipation using the Hyzen-Williams is calculated as follows:
$H_f = K.L.F.Q^{1.852}$ (3)
That in the above equation, h_f = the energy dissipation along the total length of the lateral, F= a factor relevant to the number of outflows (from the relevant table), K= a factor relevant to the diameter and material of the pipe flow rate at the beginning of the lateral regarding the number of outflows on it and the outflow is computed.
For example for sprinkler irrigation the following equations can be employed.(8,9,10,11)
$Q= N.q$ (4)
$N=INT (L/S_L+1)$ (5)
That in the above equations, N=the number of sprinklers on a lateral, q= flow rate of a sprinkler, S_L= the distance between the sprinklers on the lateral (it is assumed that the first sprinkler is located at a distance of $S_L/2$ from the beginning of the lateral), INT= the integral part.
According to the equation (3), energy dissipation along x' is computed as follows:
$H_f(x') = K.\ x'.F\ Q(x)$ (6)
By combining the equations 1, 2, 3 and 6 the following equations is obtained.
$H_f(x') = h_f (1-x/L)^{2.852}$ (7)
Through subtracting the equation (7) sides from the equation (3), the energy dissipation along x is computed as follows:
$H_f (x) = h_f [1-(1-x/L)^{2.852}]$ (8)
Regarding figure (1), if the Bernoli equation between the beginning of the lateral and a point in the length of x from it is written, the following equation is obtained:
$H_f(x)+H(x)+ \Delta Z (1-x/L)H_1+ \Delta Z$ (9)
Where H= pressure potential at the beginning of the lateral, ΔZ = height difference at the two lateral heads, H(x) = the pressure potential on a point of the lateral at the distance x from its beginning.
By combining the equations 8 and 9, following equation is obtained:
$H(x) = H_1 – h_f [1 – (1 – x/L)^{2.852}] + xS_0$ (10)
Where, S_0 = the lateral's slope (ΔZ /L)
The lateral's average pressure or working pressure of each outflow is obtained through integration from the equation (10) as follows:

$$H_a = \frac{\int_0^L H(x)dx}{L} = H_1 - 0.74h_f + \Delta Z/2 \quad (11)$$

Where H_a= average pressure in the lateral.
From the equation (11), pressure potential at the beginning of the lateral is computed as follows:
$H_1 = H_a = 0.74h_f - \Delta Z /2$ (12)
The H_a value having the outflow rate and the relation between flow rate and out flow pressure can be calculated.
The pressure potential at the end of the lateral is calculate through substitution of x=L in equation (10) as follows:
$H_2 = H_1 – h_f + LS_0$ (13)
Where H_2 = pressure potential at the end of the lateral.
Maximum pressure potential happens at the beginning or at the end of the lateral L explained later):
$H_{max} = Max (H_1, H_2)$ (14)
Where H_{max} = maximum pressure potential, Max = Maximum.
The place where minimum pressure potential happens is obtained via integration from the equation (10) and assuming it to be equal to zero as follows:

$$x_{Min} = L.\left[1 - \left(\frac{\Delta Z}{2.852h_f}\right)^{0.54}\right] \quad (15)$$

Where x_{Min} = the distance of a point of the lateral where happens the relative minimum pressure up to the beginning of the lateral.
The condition for the equation (15) answer to hold is that the ΔZ /h_f ration be less than 2.582. Otherwise the pressure potential will not have the relative minimum and alongside the lateral length the pressure potential increaser to reach its maximum at the end of the lateral.(12,13,14)
Through placing $x = x_{Min}$ in eqation (10), the minimum pressure potential is obtained as follows:

$$H_{Min} = H_1 - h_f + \Delta Z + h_f . \left(\frac{\Delta Z}{2.852 h_f} \right)^{1.54} - \Delta Z \left(\frac{\Delta Z}{2.852 h_f} \right)^{0.54} \quad (16)$$

Where H_{Min} = Minimum pressure potential.
The range of pressure changes along the lateral is equal to the difference between the minimum and the maximum pressures.
For the purpose of distribution uniformity this difference should be decreased as far as possible. Therefore, the range of pressure changes is used as the objective function in this research for the nonlinear optimization method.

$$\Delta P = H_{Max} - H_{Min} \quad (17)$$

Where ΔP is the objective function?
Decision variable is the length of the lateral since provided material, diameter, and slope of the lateral and the distance between the outflows and their flow rate is known, the only unknown of the equation (17) will be the lateral's length.
I the aim am that the objective function approaches to zero, and then a very small value is obtained for the lateral's length which is not practical. Thus, it is not necessary the objective function approaches to zero. For example in sprinkler irrigation, the objective function value is equal to 20% of the sprinkler's working pressure.
In this paper optimization has been performed using the solver optimization program in the Excel software.
In brief, it can be said that the lateral's material, diameter and slope, and the distance between the outflows and their flow rate being known, the optimized length for a lateral can be computed.

RESULTS AND DISCUSSION

All the results presented in this section hold for the $3''$ Laterals with a Hiesen – Williams's coefficient of 120 the distance between the sprinklers are of rain bird type with 1/8 inch nozzle diameter. For these types of sprinklers, the relation between the flow rate (L/s) and working pressure (m) is as follows:

$$Q = 0.0345 \sqrt{H_a} \quad (18)$$

For the purpose of studying the pressure changes along a lateral, the equation (10) is presented graphically in figure 2. This diagram is for a 400m lateral at three different slopes and flow rate of the sprinklers located on it is 0.14L/s and energy dissipation all along the lateral is 2.98m.
According to figure 2, three pressure distributions can be considered for a lateral:

Distribution type one: is the gradual decrease of pressure which happens in the laterals without slope. This gradual decrease is due to energy dissipation(15). In this type of pressure distribution, maximum pressure happens at the beginning and minimum pressure happens at the end of the lateral(16).

Distribution type two: is the gradual pressure decrease and then its increase which happens in the sloped laterals where the ΔZ /h_f is less than 2.582(17,18). In such a case there is a minimum point for the relative pressure which in figure 2 has happened(19,20).

Distribution type three: is the gradual pressure increase happening in sloped laterals where the ΔZ /h_f ratio is larger than 2.852. In this type of distribution the minimum pressure happens at the beginning of the lateral and the maximum happens at its end. In the other words it can be said that the lateral's slope overcomes the energy dissipation. In figure 2, the 0.04 slope is relevant to this distribution(21,22,23).
In all the laterals distributions should be such designed that the range of pressure changes in it does not exceed the permitted value(24).

If figure 2, for various slopes the mean pressure value is equal and can be computed from the equation (18).

Accordingly, the pressure value in the middle of the lateral for the different slopes has been obtained identical and equal to 16.1. Therefore, assuming the medium pressure to be constant, through the change of the lateral's slope, pressure at the middle of the lateral does not change. This can be proved using a combination of equations (10) and (12) and obtain the following equation for pressure in the middle of the lateral:

$$H_{L/2} = H_a - 0.12\, h_f \quad (19)$$

For the purpose of presenting a designing guide, the table 1 has been proposed. Numbers inside the table are lengths of the lateral in meter.

For better concluding from data of table 1, they can be drawn diagrammatically. For this purpose, two known flow rates have been presented in figure 3.

According to figure 3, along with the lateral's increased slope, its optimal length increases and then its inverse case happen. In fact the type two pressure distributions are changed to type three. In the type three distribution pressures alongside the lateral is constantly increased with a relatively steep slope and the difference between the minimum and maximum pressures increases. So the lateral length should be selected short so that this difference decreases.

Table 1. An example of a guide during the selection of optimal irrigation Lateral

Slope of sprinkler flow rate (l/ps)	0.001	0.004	0.006	0.008	0.01	0.015	0.02	0.04
0.12	432	491	516	547	576	175	120	60
0.14	432	473	498	517	540	586	180	80
0.16	432	468	482	504	519	564	588	110
0.18	432	456	480	492	504	540	576	140
0.2	432	455	468	480	492	528	552	185
0.22	432	456	468	480	490	516	540	245
0.24	432	452	460	468	480	504	528	443
0.26	432	448	456	468	480	492	516	577
0.28	432	446	456	468	468	492	504	564
0.3	434	445	456	463	468	483	504	552

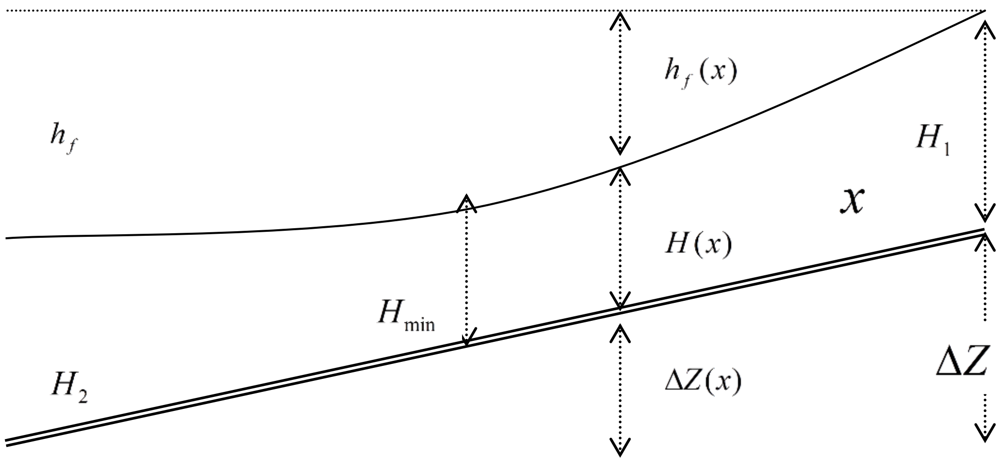

Figure 1. Lateral pressure distribution along the downhill at a constant diameter

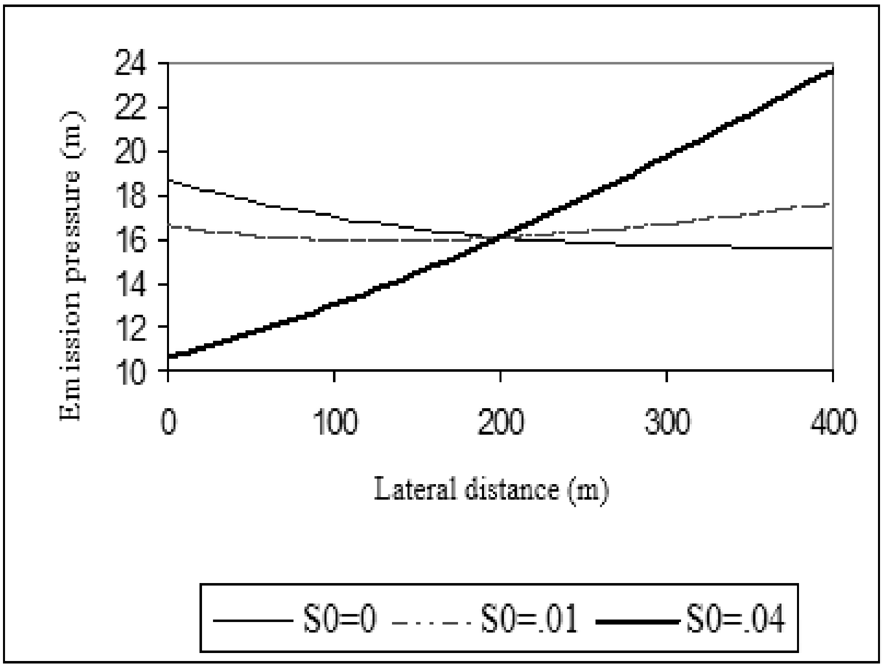

Figure 2. Lateral pressure in the different slope sprinkler.

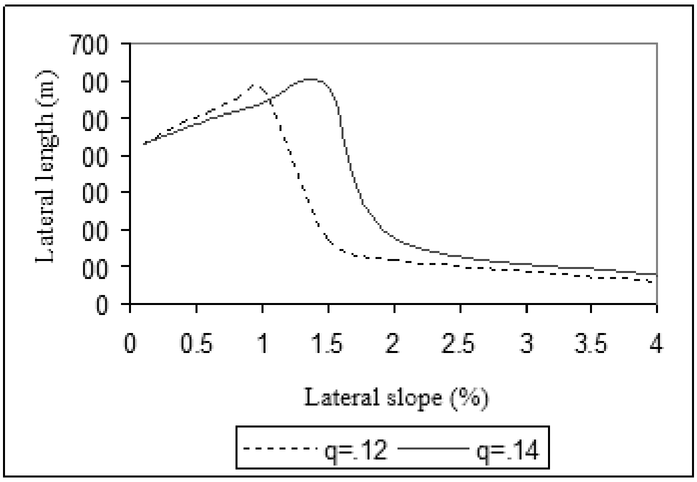

Figure 3. Evaluation of optimum lateral length than the slope changes.

Comments

It is proposed to prepare optimal design tables of laterals for types of sprinklers and in all conditions of sprinkler irrigation.

If is proposed to extend the method presented in this paper for laterals of varied diameters.

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