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Effect of Hydraulic Head and Slope on Water Distribution Uniformity of a Low-cost Drip Irrigation System

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Abstract. *Assessment of the effect of topography and operating heads on the emission uniformity distribution in drip irrigation systems is important in irrigation water management and could serve as the basis for optimizing water use efficiency and crop productivity. This study was carried out to evaluate the effect of hydraulic head and slope on the water distribution uniformity of a low-cost drip irrigation system developed by the International Development Enterprises (IDE). The drip system was tested for water distribution uniformity under varying system heads and slope conditions. The laboratory experiments were conducted at the facilities of the College of Engineering and Agro-industrial Technology, University of the Philippines Los Baños. A drum reservoir served as water supply for the IDE drip system. A sub-main of 10 m and lateral-sub holder of 10 m with adjustable slope was fabricated to enable slope variations during laboratory experiments. The drip system was operated at pre-specified operating heads of 1.0 m, 2.0 m and 3.0 m for slopes of 0%, 10%, 20%, 30%, 40% and 50% for the sub-main and 0% slope for the laterals. The discharge in each emitter was monitored for each chosen slope through direct volumetric measurements. The water distribution uniformity was then evaluated using the Christiansen's method and the Merriam and Keller's method. Mathematical relationships were then developed to characterize the effect of slope and heads on uniformity coefficient. On the basis of the results, appropriate recommendations were formulated to minimize non-uniformity of water distribution under field conditions in sloping drip-irrigated lands.*

Keywords. Drip irrigation, uniformity coefficient, emission uniformity, Christiansen's method, Merriam and Keller's method

Introduction

The use of drip irrigation for crop production in upland watersheds poses the issue of how water distribution uniformity is affected by slope and operating head. In view of the undulating or sloping topography, the irrigation engineer attempting to plan, design, install and operate a drip irrigation system in upland areas is faced with the problem of what operating head to employ for the given slope to maximize the irrigation water distribution uniformity, while taking into account other practical considerations, and consequently maximize crop yield and crop production in the entire irrigated area.

Basic hydraulic principles state that drip emitter discharge is an exponential function of emitter head. Owing to friction and minor losses along the pipeline as water is conveyed from the source to the emitters, the actual head at the emitters will be variable throughout the system. Under sloping conditions, this variable head distribution in the system becomes even more pronounced leading to non-uniform water distribution.

World-wide, various types and models of drip or micro-irrigation have evolved. Aside from the basic technical differences, they differ in cost or affordability and in water distribution uniformity. Among the most cost-effective of these models is the drip kit developed by International Development Enterprises (IDE). The drip kit consists of microtube emitters inserted through plastic tape roll laterals connected to polyethylene submain pipes which in turn can be connected to a drum water reservoir. The system can be operated by elevating the drum reservoir at appreciable head, thereby eliminating the need for a pumping unit. Typical operating heads of the IDE drip kits range from 1.0 m to 3.0 m (Keller, 2002).This drip irrigation technology is suitable for developing countries because of its low cost and simplicity of design and installation. It has started gaining popularity in some upland watersheds in the Southeast Asian countries of the Philippines, Vietnam and Indonesia for vegetable production under agroforestry systems (Reyes, 2007)

While distribution uniformity studies of some types of drip or trickle irrigation systems have been undertaken (e.g. Capra and Scicolone, 1998), evaluation of the performance of low-cost drip irrigation systems such as that of IDE at different heads for a given slope has not been fully explored. In fact, no rigorous study has been carried out to determine recommendable operating heads for such low-cost drip systems to generate certain levels of water distribution uniformity especially under sloping conditions. This study was conducted to determine the effect of hydraulic head and slope on the water distribution uniformity of the IDE ‘Easy Drip Kit’ and subsequently develop mathematical relationships to characterize the effect of slope and head on water distribution uniformity which can serve as the basis for optimizing water use efficiency and crop productivity.

Materials and Methods

The 100 m^2 IDE drip kit with a lateral length of 10 m and submain length of 10 m was used in this study. The laboratory experiments were conducted at the facilities of the College of Engineering and Agro-industrial Technology (CEAT), University of the Philippines Los Baños. The drip system was tested using an operating head of 1.0 m, 2.0 m and 3.0 m with respect to the junction of the first lateral on the upstream side, at submain slopes of 0%, 10%, 20%, 30%, 40% and 50% while maintaining 0% lateral slope. The laterals were 1 m apart. Each of the ten (10) laterals had thirty three (33) evenly-spaced emitters for a total of 330 emitters for the whole system at an emitter spacing of 30.3 cm. For each setting, emitter discharge was determined through direct volumetric measurements from eleven (11) emitters in each lateral for a total of

110 samples. Three replications were done for each slope and head setting for a total of at least 54 laboratory experiments on top of preliminary testing at 0% slope using smaller incremental head. Figure 1 shows a picture of the experimental set-up used in this study.

The discharge data were used for evaluating the water distribution uniformity. Two indices of uniformity were used in this study, namely the Christiansen's coefficient of uniformity and the Merriam and Keller's emission uniformity.

The Christiansen's coefficient of uniformity (Christiansen, 1942; Zoldoske and Solomon, 1988) can be expressed as

$$\mathbf{UC} = \left(\mathbf{1} - \frac{\mathbf{D}}{\mathbf{M}}\right)\mathbf{100} \qquad (1)$$

where:

UC = coefficient of uniformity (%)

D = average of the absolute values of the deviation from the mean discharge

$$= \frac{1}{n}\sum_{i=1}^{n}\left|X_i - M\right|$$

M = average of discharge values

$$= \frac{1}{n}\sum_{i=1}^{n} X_i$$

X_i = emitter discharge

n = number of observed discharge values

On the other hand, the emission uniformity of Merriam and Keller (1978) can be expressed as

$$\mathbf{EU} = \left(\frac{q_{LQ}}{q_{mean}}\right)\mathbf{100} \qquad (2)$$

where:

EU = emission uniformity (%)

q_{LQ} = average of the lowest quarter of the observed discharge values

q_{mean} = average of discharge values

On the basis of the results, simple mathematical relationships were developed to relate uniformity coefficient with slope at various heads and with head at various slopes.

Results and Discussion

Water Distribution Uniformity at 0% Slope

In order to serve as a basis for determining the practicable head differential to use for the various slopes in the laboratory experiments, preliminary testing of the performance of the 100 m^2 IDE drip kit at 0% slope was first performed using 0.5 m head differential. Results of the experiments for this setting are shown in Table 1.

It is apparent that both the coefficient of uniformity (UC) and the emission uniformity (EU) generally increased slightly with increasing head up to 3.0 m, beyond which the uniformity slightly decreased. However, it is also evident that neither the coefficient of uniformity nor the distribution uniformity differed substantially for a 0.5 m change in head. In fact, a two-tailed t-test at 5% level of significance showed that there is no significant difference in the mean values of UC between 1.0 m and 1.5 m of head, 1.5 m and 2.0 m, 2.5 m and 3.0 m, and 3.0 and 3.5 m. There is only a slightly significant difference between the mean UC at 2.0 m and 2.5 m heads. The same is true for the emission uniformity EU. Hence, for practical purposes a head differential of 1.0 m was used in the succeeding laboratory experiments.

It is also apparent from Table 1 that the maximum UC of 71% and maximum EU of 53.5% occur at a head of 3.0 m when the drip system is laid on a level surface. Heads lower or higher than 3.0 m yielded slightly lower UC and EU. Higher heads over 3.5 m were not attempted in this study for practical purposes. A maximum head of 3.0 m is deemed feasible not only under laboratory conditions especially for high slopes but also under field conditions from the standpoint of system installation and operation. Hence, from both hydraulic and practical standpoints, an operating head of 3.0 m reckoned from the junction of the most upstream lateral may be considered as optimum when the drip system is laid on a level surface.

Effect of Hydraulic Head on Water Distribution Uniformity

Results demonstrating the effect of head on UC and EU at various slopes are shown in Figures 2 and 3. It is apparent that higher heads lead to higher uniformity of water distribution regardless of slope. Based on the results, the maximum water distribution uniformity occurs when the operating head is set at 3.0 m. Also notable in these figures is that UC generally increases linearly with head. However, results are limited only to a maximum head of 3.0 m, again for practical purposes.

In the case of emission uniformity (EU), results show that increasing head also leads to increasing EU values. However, because of the high sensitivity of this parameter to low discharge values, the effect of head is more pronounced only under small slopes. Experimental data shows that the minimal discharge values occur at the upstream laterals when the slope is increased beyond 20%. Since EU takes into account the lowest one-fourth of the discharge data, EU values are pulled down substantially at submain slopes steeper than 20%.

For any slope, however, an operating head of 3.0 m may be considered to be optimum from both hydraulic and practical points of view.

Effect of Slope on Water Distribution Uniformity

The effect of slope on coefficient of uniformity and emission uniformity at various heads is depicted graphically in Figures 4 and 5. It is evident from these figures that water distribution uniformity decreases substantially with increasing submain slope regardless of operating head. As shown in Figure 4, the coefficient of uniformity generally decreased linearly with increasing slope. Although a slight departure in linear trend occurred between 0% and 10% slope at a head of 3.0 m, a two-tailed t-test at 5% level of significance showed that there is no significant difference between the mean UC values of 71% and 72.9 % at 0% and 10% slopes, respectively.

In the case of EU, on the other hand, the emission uniformity dropped abruptly for increasing slopes. As evident in Figure 5, for heads of 3.0 m and 2.0 m, the EU dropped to below 30% and 10%, respectively when the submain is laid on a 20% slope. Further decrease in EU was observed when the submain slope was increased. Closer analysis of data shows that higher submain slopes lead to minimal or even zero discharge at the upstream laterals and greater discharges at the downstream laterals thereby causing substantial non-uniformity of water distribution. The emission uniformity, EU, is a highly sensitive parameter and considers only the lowest one-fourth of observed discharges in relation to the mean discharge as a gage of uniformity. Hence, when close to one quarter of the data are exceedingly low due to minimal or zero discharge, the value of EU decreases tremendously. This is unlike the coefficient of uniformity which considers all observed discharge values in relation to the mean. Thus, the values of EU are relatively lower than UC for all settings of slope and head.

Mathematical Relationships between Water Distribution Uniformity and Head or Slope

To generate some predictive models for water distribution uniformity as a function of either head or slope, simple linear regression analysis was employed capitalizing on the linear trend observed between the said parameters as previously discussed. However, focus was made on the Christiansen's coefficient of uniformity instead of Merriam and Keller's emission uniformity owing to a better linear trend in the results of UC compared to EU. As evident in Figures 2 and 4, UC is more linearly related to either head or slope compared to the more sensitive EU shown in Figures 3 and 5.

Moreover, as far as design is concerned, the choice of water distribution parameter is not critical. In fact, any of the measures of water distribution uniformity may be used for design purposes as suggested by Barragan et al. (2005). In their study, it was demonstrated that EU, UC and other measures of water distribution uniformity are highly correlated with each other, making any of them eligible as a design criterion. Hence, for purposes of developing mathematical relationships or models for drip irrigation system planning and design, the use of UC over EU should not pose any problem.

Table 2 shows the results of the linear regression analysis between UC and head. All linear regression models exhibited relatively high explained variance ranging from 0.722 to 0.997 except for the case when the submain slope is 0%, whose linear regression model yielded a relatively low explained variance of 0.233. While most of the models are able to explain the variation substantially, the low R^2 of the model for 0% slope is attributable to the slight decrease in UC from 70% to 65% at a head of 2.0 m and 2.5 m, respectively, which caused some non-linearity in the middle. This drop in UC may have been due to possible emitter clogging prior to the experiments and hence may be more of an exception rather than the rule. The models for 10% up to 50% slope may prove useful for predicting the coefficient of uniformity of the IDE drip system when the operating head with respect to the junction of the most upstream lateral is set between 1.0 m and 3.0 m.

Table 3 shows the results of the linear regression analysis between UC and submain slope. All three linear regression models exhibited appreciably high explained variance ranging from 0.85 to 0.99. These models may prove useful in predicting UC when the submain slope is between 0% and 50% for heads of 1.0 m, 2.0 m and 3.0 m with respect to the first lateral junction.

Conclusion

The results of this experiment show that the water distribution uniformity of the low-cost drip irrigation kit developed by International Development Enterprises (IDE) is influenced by hydraulic head and slope. The coefficient of uniformity, UC, and the emission uniformity, EU, generally increase with increasing heads and decrease with increasing slope. The coefficient of uniformity generally follows a linear relationship with either head or slope. The UC and EU decrease substantially at submain slopes steeper than 30%. For a level surface, a head differential of 0.5 m does not cause significant change in either UC or EU. For all slopes, a head of 3.0 m with respect to the junction of the most upstream lateral may be considered to be optimum from both hydraulic and practical standpoints. Linear regression models relating UC and either head or slope may be used for predicting water distribution uniformity for heads between 1.0 m and 3.0 m and for slopes between 0% and 50%.

To minimize non-uniformity of water distribution in sloping fields irrigated by the IDE drip kit of the microtube type, the use of control valves to regulate pressure and discharge along the submain may be considered to even up the pressure distribution along this line. Hence, we recommend that IDE include affordable pressure regulator control valves for use with the kit on steep slopes. Furthermore, we recommend that IDE inform users that the IDE Easy Drip Kit is applicable on flat slopes or terraced land.

While the results of this study are limited to the range of head and slope values considered, it has nonetheless generated information that may prove useful in the planning, design, installation and operation of low-cost micro-tube type drip irrigation systems in upland watersheds for sustainable crop production purposes.

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Table 1. Coefficient of Uniformity and Emission Uniformity at Various Heads at 0% Slope

Head	Coefficient of Uniformity, UC (%)				Emission Uniformity, EU (%)			
(m)	1	2	3	Mean	1	2	3	Mean
1.0	67.0	62.5	64.8	64.8	52.1	38.9	44.0	45.0
1.5	70.7	68.7	70.1	69.8	50.8	50.3	50.0	50.4
2.0	72.6	66.8	70.2	69.9	56.1	46.9	49.8	51.0
2.5	65.2	62.9	65.7	64.6	46.8	38.1	46.5	43.8
3.0	72.5	70.5	70.1	71.0	55.1	53.6	51.8	53.5
3.5	72.2	67.6	71.4	70.4	53.2	45.5	51.4	50.0

Table 2. Linear regression models between UC and head at various slopes.

Slope (%)	Linear Regression Model*	R^2
0	Y=1.50X + 65.02	0.23
10	Y=19.90X + 15.06	0.98
20	Y= 8.67X + 24.09	0.99
30	Y = 8.32X + 20.25	0.93
40	Y=4.14X + 12.98	0.72
50	Y = 1.35X + 8.37	0.99

* Y = coefficient of uniformity, UC (%)
X = head (m)

Table 3. Linear regression models between UC and slope at various heads.

Head (m)	Linear Regression Model*	R^2
1.0	Y= -0.95X + 54.69	0.85
2.0	Y= -1.15X + 68.57	0.99
3.0	Y= -1.27X + 77.91	0.94

* Y = coefficient of uniformity, UC (%)
X = submain slope (%)

Figure1. The experimental set-up for testing the drip irrigation system

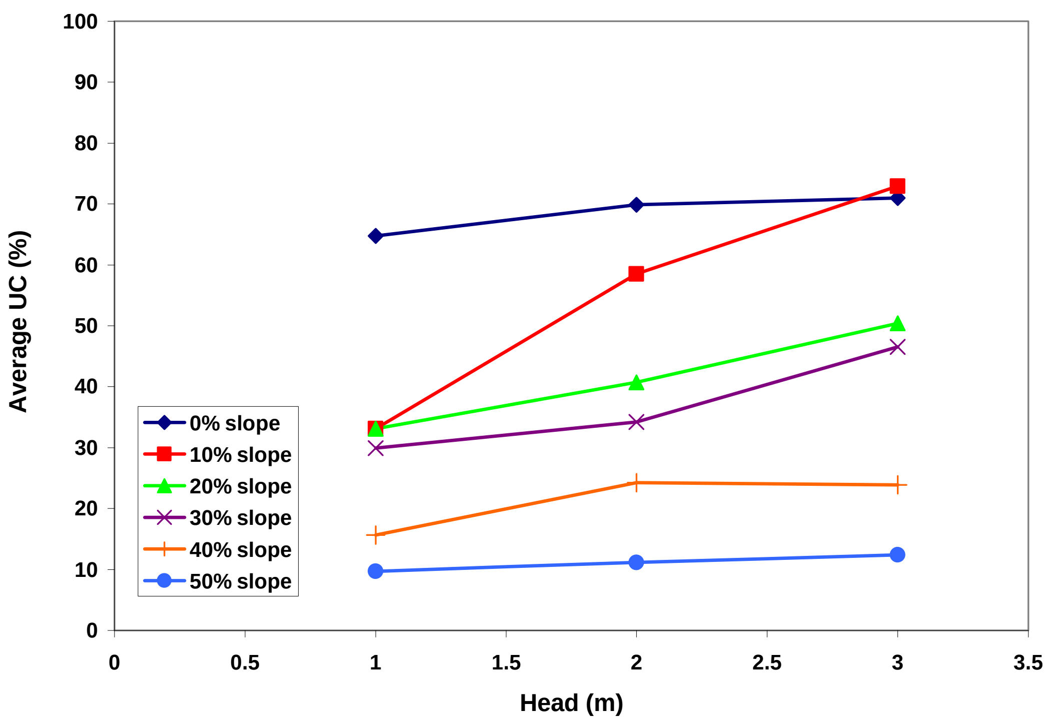

Figure 2. Effect of Head on Coefficient of Uniformity at Various Slopes

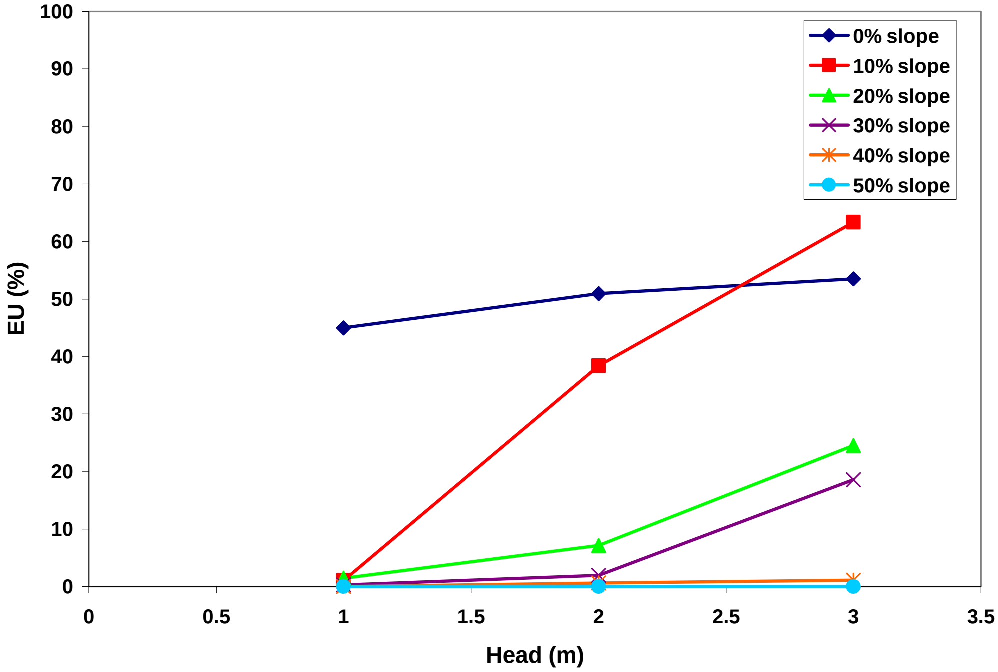

Figure 3. Effect of Head on Emission Uniformity at Various Slopes

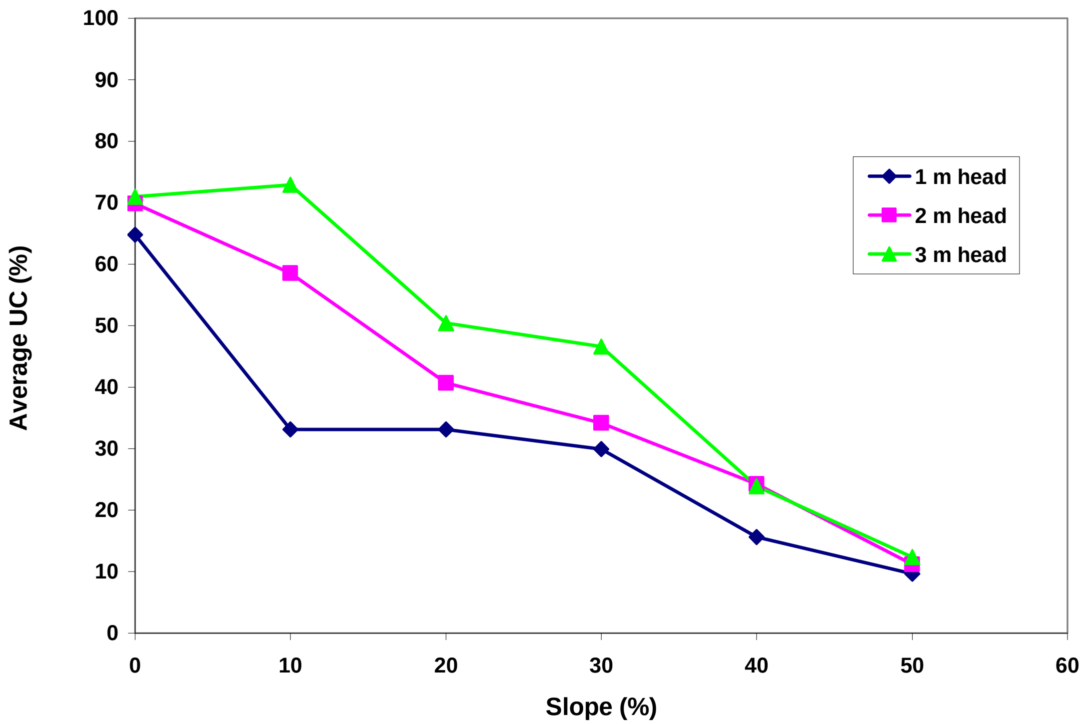

Figure 4. Effect of Slope on Coefficient of Uniformity at Various Heads.

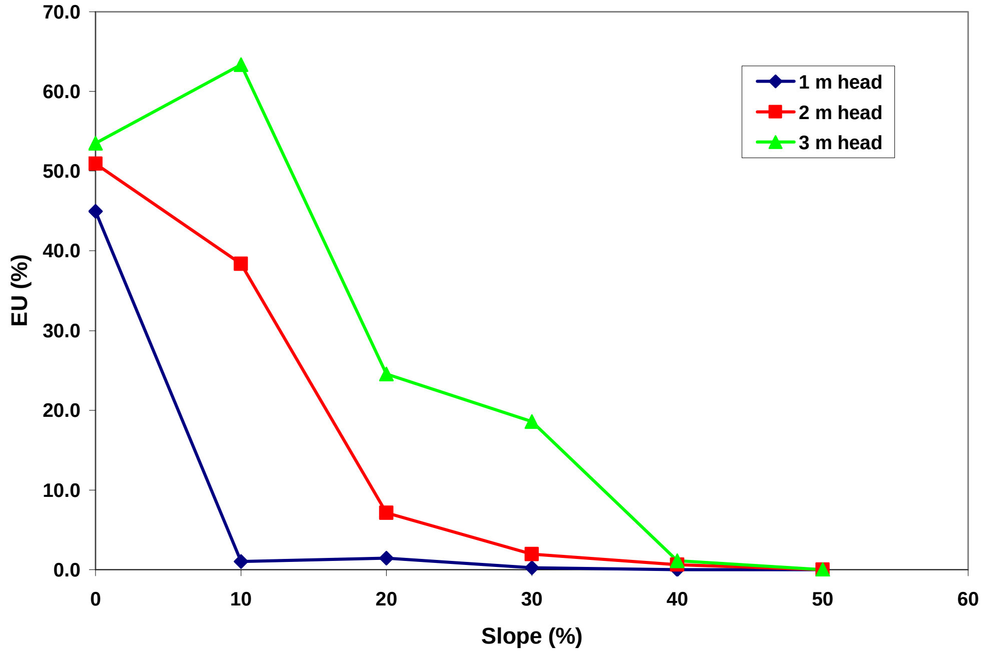

Figure 5. Effect of Slope on Emission Uniformity at Various Heads