Analysis of Manning's and Drag Coefficients for Flexible Submerged Vegetation

Khamaruzaman Wan Yusof[1], Muhammad Mujahid Muhammad[1,2], Muhammad Raza Ul Mustafa[1], Nor Azazi Zakaria[3] and Aminuddin Ab. Gahani[3]

[1]Department of Civil & Environmental Engineering, Universiti Teknologi Petronas (UTP), Seri Iskandar, Malaysia.
[2]Department of Water Resources & Environmental Engineering, Ahmadu Bello University, Zaraia – Nigeria.
[3]River Engineering and Urban Drainage Research Centre (REDAC), Universiti Sains Malaysia (USM) Pinang, Malaysia.

khamaruzaman.yusof@utp.edu.my

Abstract. Accurate determination of flow resistance is of great significance in modelling of open channels that will convey water efficiently. Although, resistance or drag induced by vegetation have been systematically studied for several decades, estimating of the resistance remain as a challenge. This is because most of previous studies use artificial vegetation to investigate flow – vegetation interactions. To overcome this, the present study evaluates the vegetation resistance in terms of Manning's roughness coefficient and drag coefficient using a natural flexible vegetation (cow grass) under submerged condition. From the experimental result obtained, it was observed that the Manning's and drag coefficients decreased with the increasing in average velocity. Also, graphical relationship between Manning's coefficient, n and drag coefficient, C_D has been developed with $R^2 = 0.9465$, which indicate that there exist a strong correlation between n and C_D, and one can use the proposed graphical model to predict the n - values corresponding to the C_D – values.

1. Introduction

Flow resistance induced by vegetation have been systematically studied for several decades, estimating of the resistance remain as a challenge. This is because most of previous studies use synthetic vegetation to investigate flow – vegetation interactions.

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Thus, for accurate determination of flow resistance, the present study employed the use of natural flexible vegetation, as it is of great significance in modelling of open channels that will convey water efficiently. Also, if the estimated roughness is too low, this can result in over – estimating the discharge, under – calculating the flood levels, and consequently, over - design of drainage facilities with excessive expenditure in erosion control works and vice versa [1]. However, the estimation of this roughness, n, depends on several factors as illustrated by Chow [2], that the value of n is highly variable which can be affected by the following: surface roughness, vegetation, channel irregularity, channel alignment, silting and scouring, obstruction, and stage and discharge. From these factors, vegetation resistance is of very significant in predicting n, as it has large Manning's coefficient, n, compared to other factors, depending on the height, density, distribution and type of vegetation.

Furthermore, another important parameter that can be related with flow resistance is the drag on vegetation, this is because the vegetal drag increases the overall flow resistance and decreases the bed shear stress of the channel, causing in reduction for bed-load transport capacity. Hence, the drag improved tendency for trapping, deposition, and stabilization of sediments. Numerous methodologies have been proposed to model the effects of vegetation on open-channel flow and sediment transport [2-7]. Also, vegetation-induced drag force has been comprehensively investigated in recently by Kothyari, Tang, Wu and others [8-10].

The evaluation of the vegetation resistance in terms of Manning's roughness coefficient and drag coefficient is therefore the main objective of this study. A laboratory experiments was conducted to assess the flow resistance as well as the drag coefficient using a natural flexible vegetation (cow grass) under submerged condition.

2. Flow resistance due to flexible vegetation

The flow resistance in channels with flexible vegetation can be determined using relative roughness method similar to the commonly used resistance relationships derived for rigid roughness in pipes and channels [11, 12]. In this regard, Kouwen and Li [13] suggested that the Darcy-Weisbach friction factor, λ, can be found using a semi-logarithmic resistance equation also known as the Colebrook-White equation:

$$\frac{1}{\sqrt{\lambda}} = a + b\log(R/k) \tag{1}$$

Where k is the roughness height of the vegetation, R = hydraulic radius of the channel, a and b two fitted parameters that are found to be dependent on the relative magnitude of the shear velocity *U and a critical value U*crit. Also, based on numerical model test, Darby [5] used a general approach to evaluate the roughness of vegetation and movable bed:

$$\frac{1}{\sqrt{\lambda}} = 2.03\log\left(\frac{a_s R}{k}\right) \tag{2}$$

$$a_s = 11.0(R/h_{max})^{-0.314} \tag{3}$$

Where, as is a non-dimensional shape correction factor and hmax being the maximum flow depth in the cross section. For flexible submerged vegetation, the roughness height, k, is a function of the amount of drag exerted by the flow and the flexural rigidity MEI [13]:

$$k = 0.14h_v \left[\frac{(MEI/\tau)^{0.25}}{h_v}\right]^{1.59} \tag{4}$$

Where, τ = bed shear stress, MEI is the flexural rigidity and hv is vegetation height. Using laboratory experiments, Kouwen [14] and Temple [15] developed empirical equations to compute the MEI with vegetation height, hv, for a variety of growing and dormant grass species as follows:

$$MEI = \begin{cases} 319h_v^{2.3} & \text{for green, growing grass} \\ 25.4h_v^{2.26} & \text{for dormant or dead grass} \end{cases} \tag{5}$$

Also, the vegetation roughness can be determined in terms of the popularly known Manning's roughness, n, using Manning's equation. Thus, in this work the Manning equation would be adopted for being the usual method for estimating energy losses in hydraulic modelling:

$$\mathrm{Q} = \frac{1}{\mathrm{n}}\mathrm{A}R^{2/3}\mathrm{S}_0^{1/2} \tag{6}$$

Where, Q = discharge (m^3/s), A = cross-sectional area (m2), R = hydraulic radius (m) = A/P, P = wetted perimeter (m), and S = slope of gradient of the bed.Please follow these instructions as carefully as possible so all articles within a conference have the same style to the title page. This paragraph follows a section title so it should not be indented.

3. Drag coefficient for submerged vegetation

The drag in vegetated channel is determined based on the concepts suggested by Wu et al. [10]. Noting that, it is challenging to represent a vegetation element with simple geometry because of its irregularity in shape. Thus, as an approximation, a vegetation stem is conceptualized as a cylinder with height, h, and a representative diameter, D. The procedure to calculate the vegetative drag coefficient due to submerged vegetation is represented as follows:

$$F_G = F_D + F_S \tag{7}$$

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Where, FG is the gravitational force, FD is the drag force exerted on the vegetation and FS is the surface friction of the sidewalls and bottom.
In which the gravitational force FG is expressed as:

$$F_G = \rho . g(B.H.L).S \tag{8}$$

Where, ρ is the mass density of water (Kg/m^3), g is the gravity constant (m2/s), H is depth of water above the vegetation, B is channel width (m), S is the bed slope (m/m) and L is length of vegetated channel reach. For uniform flow in vegetated channel, FS is negligible compared to FD. The drag force FD is given by:

$$F_D = C_D(\lambda . h_v . B.L)\frac{\rho . U^2}{2} \tag{9}$$

Where, hv is height of vegetation, and C_D is the drag coefficient, λ is the vegetal area coefficient representing the vegetation density per unit channel length (m-1). Equating FG and FD gives:

$$C_D = \left(\frac{H}{h_v}\right)\frac{2.g.S}{U^2\lambda} \tag{10}$$

Equation (10) can be used to evaluate the vegetal drag coefficient C_D, which accounts for the features of vegetation, as indicated above. Also, it should be noted that vegetation density, λ, was determined based on concept of Jihong and Launia [16], that vegetation density can be generally considered as the momentum absorbing area per unit water volume taking into account the whole part of the plant, which is more elaborate than defining it as the projected area of rods per unit volume.

4. Experimental work

The laboratory experiments were conducted in a man - made concrete rectangular channel of dimension 16 m overall length, 1.5 m width and 1 m depth respectively, located at the physical modeling laboratory of River Engineering and Urban Drainage Research Center (REDAC), Universiti Sains Malaysia (USM). It consists of three sections which were the inlet sump, the test flume (12 m length) and the outlet sump. Fig. 1 shows the plan view of the test channel with the Cow grass planted on a bed slope of 1 in 1000. Also, the figure shows the various measurement locations.

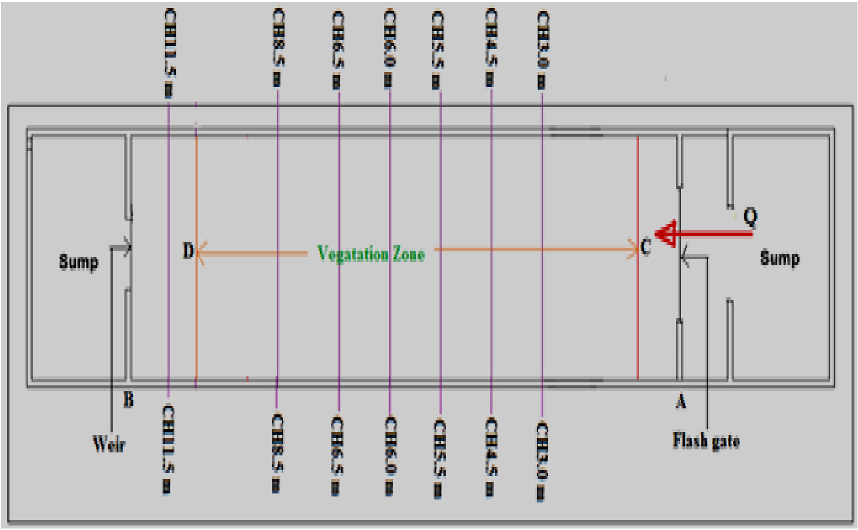

Figure 1. Plan view of test channel

From Figure 1, the Cow grass planted over a length of 10 m in the vegetated zone labeled CD. The average height of the grass was maintained at 50 mm. Afterwards the experimental testing started using three different flow depths with the grass under submerged conditions. The varied flow depths were y = 0.15 m, y = 0.20 m and y = 0.40 m, respectively. Velocity Distributions were determined at five different vertical points (that is width of channel 1.5 m divide by 5 equals 0.3 m) measured along 7 – cross sections labelled CH3.0 m as the first cross section, meaning 3.0 m away from the inlet, similarly cross section CH4.5 m, means 4.5 m away from inlet and so forth, up to CH11.5 m as shown in Fig. 2. Also, at each point, 8 different depths were measured in fractions of the flow depths, that is, 0.2y, 0.25y, 0.3y, 0.4y, 0.5y, 0.6y, 0.7y and 0.8y, respectively. Acoustic Doppler Velocimeter (ADV) was used for the velocity measurement which can determine the velocity in x, y and z – directions as stream-wise, lateral and vertical, respectively. However, only the average vertical velocities were used for the analysis of the flow resistance. Also, the measured velocities are influenced by the particles moving along with the water which help in obtaining a better result. As such turbid water was used in this experiment.

5. Results and discussion

Tables 1 - 3 show the average vertical velocity profiles of the various flow depths. From these tables, variations of Manning's Roughness, n and drag coefficient, C_D, with Velocity were shown, where both n and C_D values decrease with increase in velocity and vice versa.

It should be noted that vegetation density, λ, in Tables 1 -3 was obtained based on the following criteria: Length of vegetation reach L_v = 10 m; Area of vegetation reach, Av = B*Lv = 15 m2, where B is the width of the channel = 1.5 m; Volume of water, $V_w = A_v*h$; and vegetation density, $\lambda = A_v/V_w$.

Table 1. Variation of manning's and drag coefficients for the flow depth, y = 0.15 m

Total Flow depth (m)	Fraction water depth, h (m)	Average Velocity, V (m/s)	Flow Area A (m^2)	Vegetation density λ (m^{-1})	Drag Coefficient C_D	Manning n
	0.03	1.42	0.05	33.33	0.000	0.001
	0.04	1.11	0.06	26.67	0.001	0.001
	0.05	0.57	0.07	22.22	0.005	0.002
	0.06	0.50	0.09	16.67	0.011	0.004
y = 0.15	0.08	1.15	0.11	13.33	0.003	0.002
	0.09	0.99	0.14	11.11	0.007	0.003
	0.11	1.07	0.16	9.52	0.008	0.003
	0.12	0.67	0.18	8.33	0.026	0.005

Table 2. Variation of manning's and drag coefficients for the flow depth, y = 0.20 m

Total Flow depth (m)	Fraction water depth, h (m)	Average Velocity, V (m/s)	Flow Area A (m^2)	Vegetation density λ (m^{-1})	Drag Coefficient C_D	Manning n
	0.04	0.37	0.06	25.00	0.009	0.003
	0.05	0.48	0.08	20.00	0.009	0.003
	0.06	0.32	0.09	16.67	0.029	0.006
	0.08	0.63	0.12	12.50	0.013	0.004
y = 0.20	0.10	0.26	0.15	10.00	0.118	0.011
	0.12	0.17	0.18	8.33	0.402	0.019
	0.14	0.16	0.21	7.14	0.590	0.023
	0.16	0.31	0.24	6.25	0.210	0.013

Table 3. Variation of manning's and drag coefficients for the flow depth, y = 0.40 m

Total Flow depth (m)	Fraction water depth,	Average Velocity,	Flow Area	Vegetation density λ (m^{-1})	Drag Coefficient	Manning n

	h (m)	**V (m/s)**	**A (m^2)**		**C_D**	
	0.08	0.45	0.12	12.50	0.025	0.005
	0.10	0.44	0.15	10.00	0.042	0.006
	0.12	0.32	0.18	8.33	0.112	0.010
	0.16	0.34	0.24	6.25	0.182	0.012
y = 0.20	0.20	0.09	0.30	5.00	3.955	0.056
	0.24	0.10	0.36	4.17	4.299	0.056
	0.28	0.14	0.42	3.57	3.300	0.047
	0.32	0.12	0.48	3.13	5.787	0.060

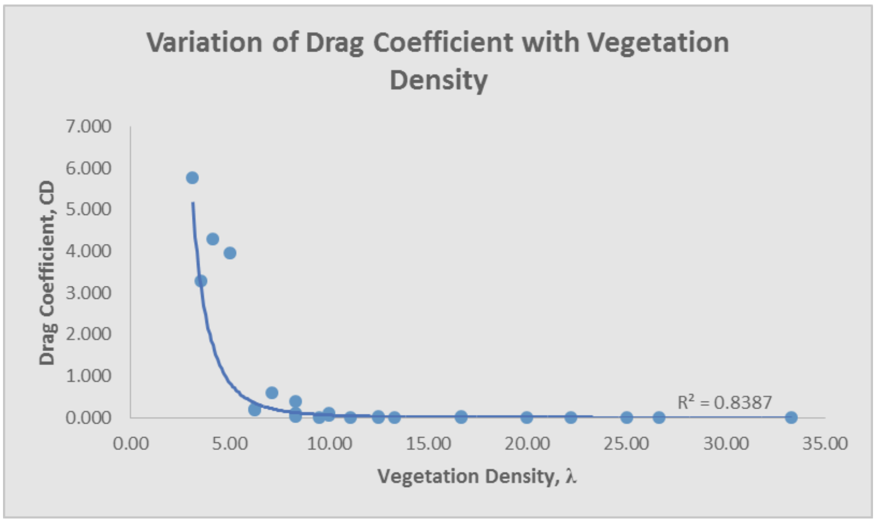

Figure 2. Variation of drag coefficient with vegetation density

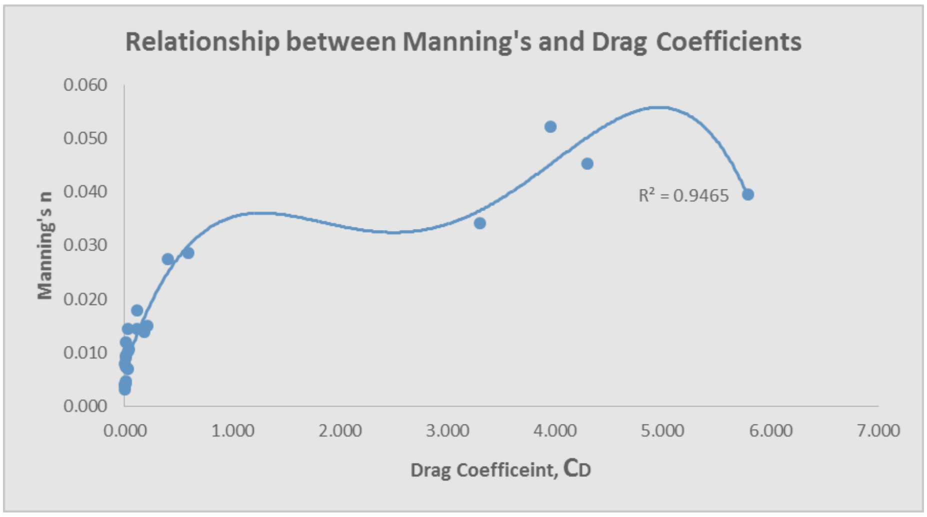

Figure 3. Relationship between manning's and drag coefficient

Also, using the above tables, Figures 2, 3 and 4 were plotted to illustrate the overall relationship between C_D and vegetation density λ, Manning's n with C_D and n-V relationships respectively, for the combined depths. From these Figures, it shows that the drag C_D, has a very good relation with the Manning's n, and λ, as the correlation coefficient R^2 is generally more than 80%. Similarly, from Figure 4 there exist a strong relations as R^2 is more than 90%. And Figure 5 shows the overall velocity distributions with good correlation of R^2 = 70%. Hence, these curves obtained can be used for the design of channel stability or its capacity in vegetated waterways [17].

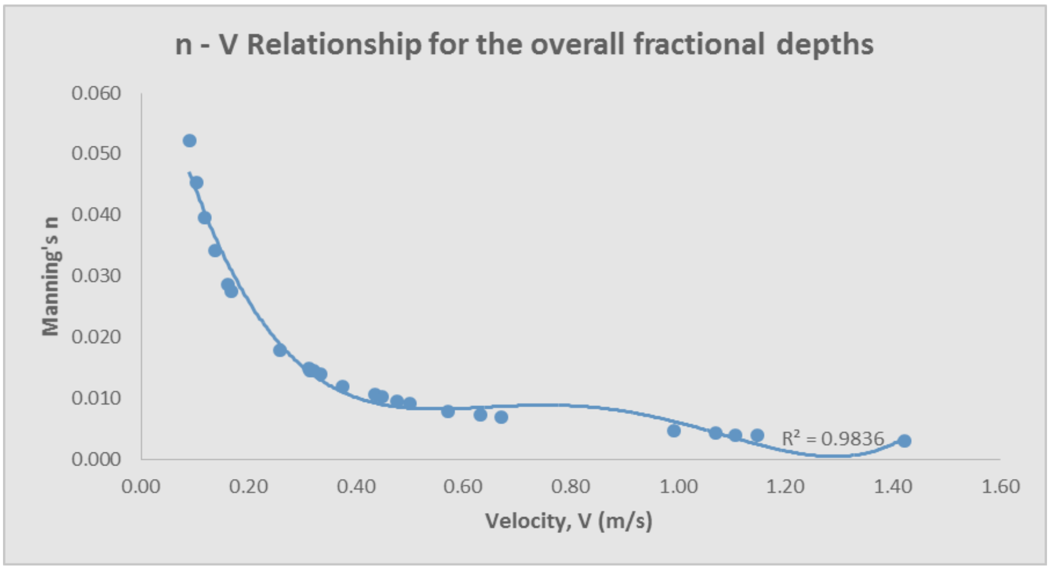

Figure 4. Relationship between manning's and velocity

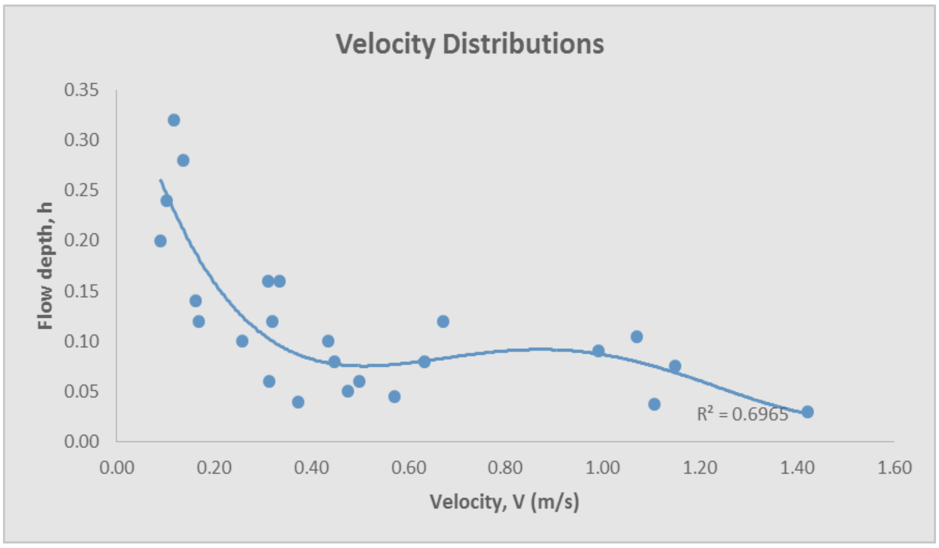

Figure 5. Overall velocity distributions

6. Conclusion

An investigation on flow resistance and drag coefficient has been carried experimentally using natural vegetation to study the variation of vegetation resistance based on Manning's coefficient with flow velocity, depth and drag coefficient, for submerged condition only. It was deduced that the Manning's and drag coefficients decreased with the increasing in average velocity. Also, graphical relationship between Manning's, n and drag, C_D has been developed with R^2 = 0.9465, which indicate that there exist a strong correlation between n and C_D. Thus, the curves can be applied in construction of vegetated channels.

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