Calculating Drag Coefficient of Different Submerged Vegetation Densities in Open Channel

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ABSTRACT - In this paper, the effect of submerged vegetation resistance using movable bed surface were studied. Rigid linear cylindrical artificial vegetation of three different densities of 40 stem/m^2, 80 stem/m^2 and 100 stem/m^2 were used. Three discharges of 15 l/s., as a maximum obtained flow, 13 l/s and 8 l/s with three water depths of 14 cm, 16 cm and 18 cm were applied. According to Kleinhans (2008), for submerged vegetation case, the used stem height is 4 cm to give h/k (water depth-stem height ratio less than 5. Water velocities were measured using Acoustic Doppler Velocimeter (ADV) instrument in the centerline of channel along the vegetation zone (8.0 m long). The vegetation drag coefficient as the major flow resistance was computed. Comparative study was done in this research between Huthoff (2007) model and the obtained experimental results. Klopstra et al. (1997) model was used to compute the average water depth velocity. Baptist et al. (2006) approach was modified to give an empirical equation using the experimental data that gives an agreement with Huthoff (2007) model. Then, the apparent drag (CD) was computed using Huthoff (2007) model and compared with the obtained drag from the deduced empirical equation from the experimental work.

Key words: Flow resistance, Submerged vegetation, Drag coefficient, Water velocity.

1. INTRODUCTION

For simulation of ecological functions through rivers and flood management; it's important to predict the flow resistance caused by the presence of vegetation. The presence of vegetation causes many affects such as decreasing the velocity of water and consequently the corresponding bed shear stress, then the quantity of sediment transport could be decreased. In general, vegetation resistance decreases the local scour as increasing the global hydraulic roughness (Tsujimoto and Kitamura, 1990 and Bennett et al., 2008 and Galema, 2009).

According to Kleinhans (2008), there were three known categories for vegetation according to its height; first, if h>>> 5k, where, the depth of water h and the height of vegetation k, this type called well submerged vegetation. In this case, the vegetation height does not affect clearly the upper part of water velocity (surface velocity). So, Manning equation could be used to express the vegetation part as rough surface (Augustijn et al., 2008).

Second, submerged vegetation case, if k<h<5k. In this case, the water velocity column could be separated into two zones, the upper water zone (free flow) and the lower vegetation zone. The water velocity through the vegetation zone was uniform and a transition profile was found between near the top of vegetation depth and the surface water (free upper water zone).

The third category, If - h<k, emerged vegetation case. In this case, the water depth was covered by vegetation. The velocity profile in this case seems to be uniform and the roughness of bed could be neglected. The second category was studied in this research experimentally (Baptist et al., 2006).

The effect of vegetation resistance on the flow conditions was described by several approaches. For emerged vegetation case, there were three important approaches used for describing it. The deduced equation given by Petryk and Bosmaijan (1975) was considered the most important one. Also, new approaches such as Stone and Shen (2002) and Hoffmann (2004) models were developed to describe the emerged case.

For submerged vegetation category, most models and approaches based on the theory of two layers, distinguished between the velocity profile through the vegetation part and through the upper free water zone. These approaches described the water velocity through the upper part by a logarithmic profile except the description of Stone and Shen (2002).

Results of 173 runs obtained from five different authors by Galema (2009) used to evaluate the different vegetation approaches to find the suitable model that could be applied to describe the vegetation resistance.

A comprehensive study by Vargas-Luna et al. (2016) was done to evaluate the effect of vegetation on the rate of sediment transport. Also, they introduced a comparative study between many descriptors and models by calculating the vegetation drag.

2. DESCRIPTION OF RESISTANCE EQUATIONS

Several approaches are presented to describe the resistance of vegetation zone.

2.1 Roughness Equations

There were different equations had been used to describe the roughness of any channel. Also, these equations could be used for modeling the vegetation zone resistance.

2.1.1. For constant roughness

Chezy (1769): In this approach, the bottom and side walls roughness for uniform flow (Chow, 1959) could be described as:

$U = C\sqrt{R\ i}$ where, U = flow velocity, R = hydraulic radius and i= slope of channel. (1)

Darcy-Weisbach (1845): The derived equation of Julius Weisbach in 1945 accompanied with the derived formula of Henry Darcy in 1858 gave the Darcy- Weisbach equation

$$U = \sqrt{\frac{8g}{f}}\sqrt{R\ i} \qquad (2)$$

where, g = gravitational acceleration, f= Weisbach roughness coefficient (from Moody diagram). Effect of inlets, elbows and other fittings (shape drag) were not represented in this approach (Brown, 2002).

Manning (1889): Manning developed formula used to describe the roughness based on experimental data verified by 1170 observations (chow, 1959).

$U = \frac{1}{n}\ R^{\frac{2}{3}}\sqrt{i}$ where, n = Manning's coefficient. (3)

Strickler (1923) derived an equation reflects the size of irregularities and roughness height.

$n = 0.04\ k_s^{\frac{1}{6}}$ In which, k_s = Strickler roughness height (chow, 1959). (4)

For wide channels, it is assumed R= h, then equations (1), (2) and (3) could be expressed as:

$$\frac{U}{\sqrt{h\ i}} = C = \sqrt{\frac{8g}{f}} = \frac{1}{n}R^{\frac{1}{6}} \qquad (5)$$

2.1.2. For roughness affected by flow characteristics

Strickler (1923): the final deduced model could be described as:

$$C = 25\ \left[\frac{R}{k_s}\right]^{\frac{1}{6}} \qquad (6)$$

Keulegan (1938): gave an equation associated with the effect of irregularities on the channel as:

$$C = 18^{10}\ \log\left(\frac{12R}{k_N}\right) \qquad (7)$$

where, k_N = Nikuradse sand grain roughness and reflects the size of irregularities on the channel bed (Brown, 2002).

Manning's coefficient used in software

De Bos and Bijkerk (1963) derived and equation of Manning's coefficient depends only on the water depth and neglecting the size of roughness.

$$n = \frac{h^{\frac{1}{3}}}{\gamma}$$ where, $\gamma =$ 33.79 for winter and $\gamma =$ 22.53 for summer (De Bos and Bijkerk, 1963). (8)

2.2 Submerged Vegetation Approaches

The most important approaches for submerged vegetation could be listed as:

Final deduced equation given by Borovkov and Yurchuk (1994) as:

$$U = \sqrt{\frac{8g\ h\ i}{f}} \qquad (9)$$

In which, = Darcy - Weisbach's friction factor. They computed this factor as:

$$\frac{1}{\sqrt{f}} = K\ \left(\frac{h}{k}\right)^{\sqrt{f}}\ \sqrt{\frac{s}{k\ d\ CD}}$$ in which, d = diameter of vegetation (stem), CD =Drage coefficient of vegetation, K = Von Karman constant and k = vegetation height (10)

Borovkov and Yurchuk (1994) presented K = 0.4 is the same as Von Karman constant which is used to describe the profile of velocity in case of turbulent steady and uniform flow.
Klopstra et al. (1997)

In this approach, the mean velocity for the total depth inside and above the vegetation is combined to yield the following equation:

$$U = \frac{k}{h}\ U_v\ + \frac{h-k}{h} U_s$$ In which, U_s = surface free water velocity of the upper part. (11)

Stone and Shen (2002): it's the most important model used for submerged vegetation case and includes the most effective parameters as:

$l^* = \frac{k}{h}$, in which l^* = stem - water depth ratio

The apparent velocity could be given as: $U = \frac{U_v}{\sqrt{l^*}}$ (12)

$$U = \sqrt{\frac{2g}{CD\ m\ d}}\sqrt{i}\ \left(1 - d\sqrt{m}\right)\ \sqrt{\left(\frac{h}{k} - \frac{1}{4}\ \pi\ d^2\ m\right)\ \frac{1}{l^*}} \qquad (13)$$

Van Velzen et al. (2003) approach could be described as:

$U_v = \sqrt{\frac{2g}{CD\ m\ d}}\ \sqrt{i}$, as the water velocity through the vegetation layer is unaffected by the surface water velocity of the upper part. He described the upper velocity part as logarithmic equation as:

$$U_s = U_v\ +\ 18\sqrt{(h-k)\ i}\ \ \log\frac{12(h-k)}{k_N} \qquad (14)$$

In which, k_N = roughness height = $1.6k^{0.7}$. Combination of vegetation velocity and surface velocity yields:

$$U = \sqrt{\frac{2g}{CD\ m\ d}}\sqrt{i}\ +\ 18\ (h-k)^{\frac{3}{2}}\ \frac{\sqrt{i}}{h}\ \log\ \frac{12(h-k)}{k_N} \qquad (15)$$

Baptist et al. (2006) approach is considered the easier model for application for the submerged vegetation case

$$U_v = \sqrt{\frac{2g}{CD\ m\ d}}\sqrt{i}\ \sqrt{\frac{h}{k}} \qquad (16)$$

Baptist et al. (2006) did a simulation of wide variety of cylinders and water flow depths, 990 model results from simulation to find the equation of mean velocity as:

$$U = \left(\sqrt{\frac{2g}{CD\ m\ d\ k}} + \frac{\sqrt{g}}{k}\ \ln\left(\frac{h}{k}\right)\right)\sqrt{hi} \qquad (17)$$

Huthoff (2007) model: he derived an analytical equation for water velocity through and above the vegetation zone.

$$U_s = \sqrt{\frac{2\ g\ i}{CD\ m\ d}}\left(\frac{h-k}{s}\right)^{\frac{2}{3}} \text{with, } s = \frac{1}{\sqrt{m}} - d \qquad (18)$$

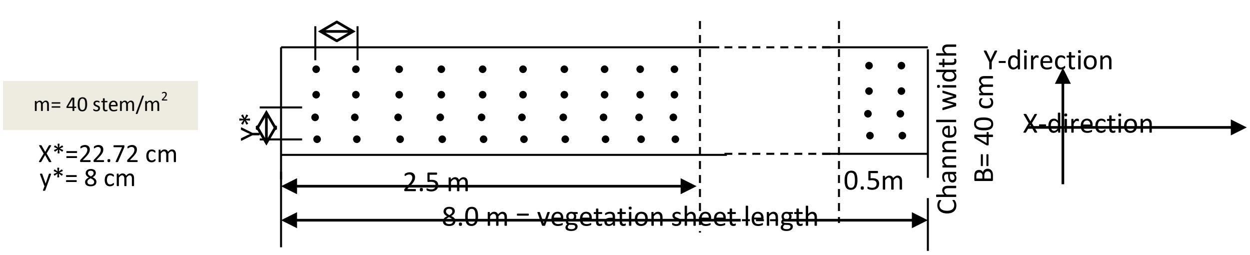
$$U = \sqrt{\frac{2gi}{CD\ m\ d}}\left(\sqrt{\frac{k}{h}} + \frac{h-k}{h}\left(\frac{h-k}{s}\right)^{\frac{2}{3}}\right) \qquad (19)$$

3. EXPERIMENTAL WORK

All experimental runs were exerted in a rectangular flume with a mild slope. The channel dimensions are 40cm× 40cm ×1200 cm long, with 200 m long Perspex sides, **Fig. (1).** This work was done in irrigation and hydraulics lab. - Faculty of engineering - El-Mansoura University.

Fig. (1): The selected apparatus

A wooden sheet with 8.0 m long and 0.40 m width, this sheet used for fixing the cylindrical stems. A coarse sand sample was put in the flume bed with 2 cm height, d_{50} = 0.620 mm, used for the whole length of channel. A cylindrical plastic stem of 1.0 cm (d) diameter with lengths (k) of 4.0 cm was used. The used number of stems was 128 for m_1 = 40 stem/m^2, 256 stems for m_2 = 80 stem/m^2 and 320 stems for m_3 = 100 stem/m^2, **Fig. (2)**



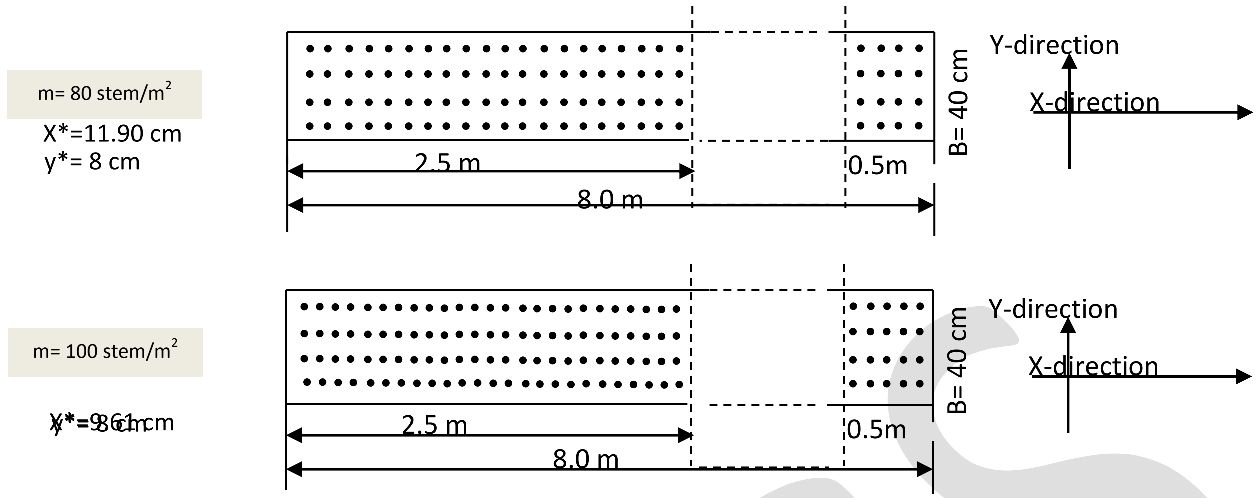


Fig. (2): Plane of the models for the selected different densities.

According to Huthoff (2007) (equation 18) for submerged vegetation; $s_1 = 0.1481$, $s_2 = 0.101$ and $s_3 = 0.09$ for the three stem densities respectively. The channel slope (i) is found to be 0.00053.

Thirty (30) runs were done as; 27 runs for submerged case and 3 runs for the case of no vegetation. Three flow depths of 14 cm, 16 cm and 18 cm were applied for flow rate 15 l/s., as maximum, 13 l/s and 8 l/s.

For each run, the water velocity through the vegetation zone was measured using ADV instrument at four points at the centerline of channel at distances of 1.6m (P_1), 3.2m (P_2), 4.8m (P_3) and 6.4m (P_4) from the inlet of the wooden plate. The average values of water velocities through the vegetation zone (U_v) and though the upper free zones (Us) were measured at the selected four points for each run.

4. RESULTS AND ANALYSIS

In submerged vegetation case, (***k*=4 cm & *k*<*h*<5*k*)** , the velocities through the vegetation zone are larger than that in emergent case due to the higher velocities in the upper free part (up to the vegetation part) affects greatly on it and causing shear in the vegetation layer to increase. A two-layer approach could be used for description this case because of the difference in velocity through the two layers, velocity vegetation layer and the upper free layer. In this approach, the velocity inside vegetation zone is separately described from the upper zone part (surface zone). All approaches in this case assumed the velocity distribution through vegetation zone is uniform but the velocity in the surface layer could be described by logarithmic profile.

Using the experimental results, an empirical equation was deduced using SPSS program and dimensionless method by modification equation (17), modified Baptist et al. (2006) approach.

This equation is:

$$U = \left(\sqrt{\frac{2g}{CD\ K}} + \frac{\sqrt{g}}{K}\ \ln\left(\frac{h}{k}\right) \right) \sqrt{0.7\ h\ i} \qquad (R^2=0.85) \qquad (20)$$

where, K = 0.4, Von Karman constant, which is used to describe the profile of velocity in case of turbulent steady and uniform flow. (Borovkov and Yurchuk, 1994)
The average velocity through the vegetation layer (U_v) and through the surface layer (U_s) were measured for each run, then equation (17) of Klopstra et al. (1997) approach is applied to compute the average velocity (U) through the whole depth (the apparent velocity). After that, a comparison between the deduced empirical equation and Huthoff (2007) approach given in equation (19) was done. Huthoff (2007) was chosen because he gives an analytical expression for bulk flow through and over vegetation.

Figures (3) through (5) illustrate the difference between the computed drag by the experimental work and Hothoff (2007) model for the vegetation density of 100 stem /m^2, 80 stem /m^2 , 40 stem /m^2 respectively at flow depths of 18 cm and 14 cm.

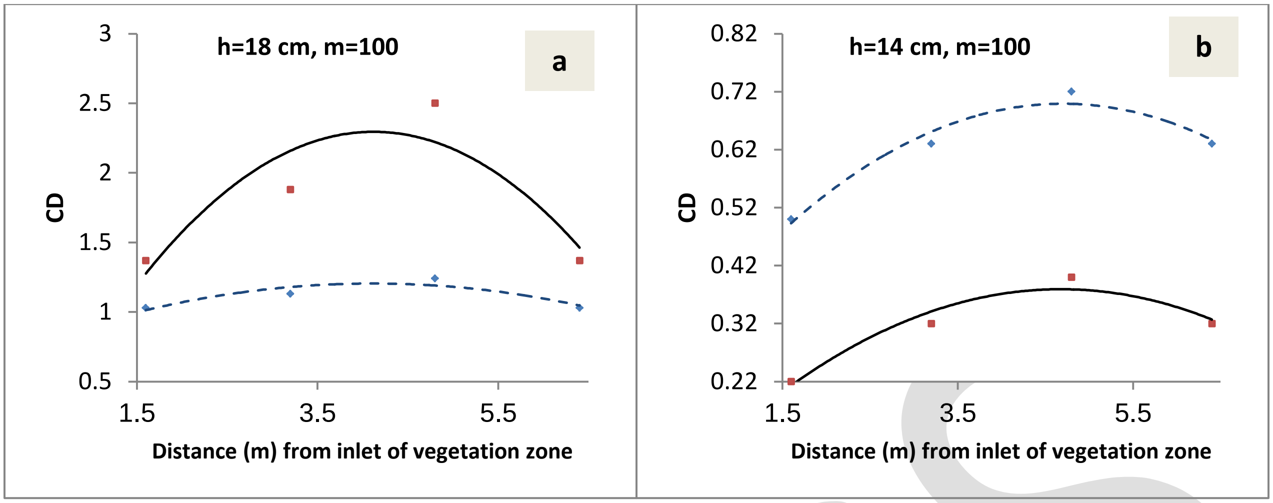


Fig. (3): Difference between Hothoff (2007) and the experimental work for m=100 stem /m^2

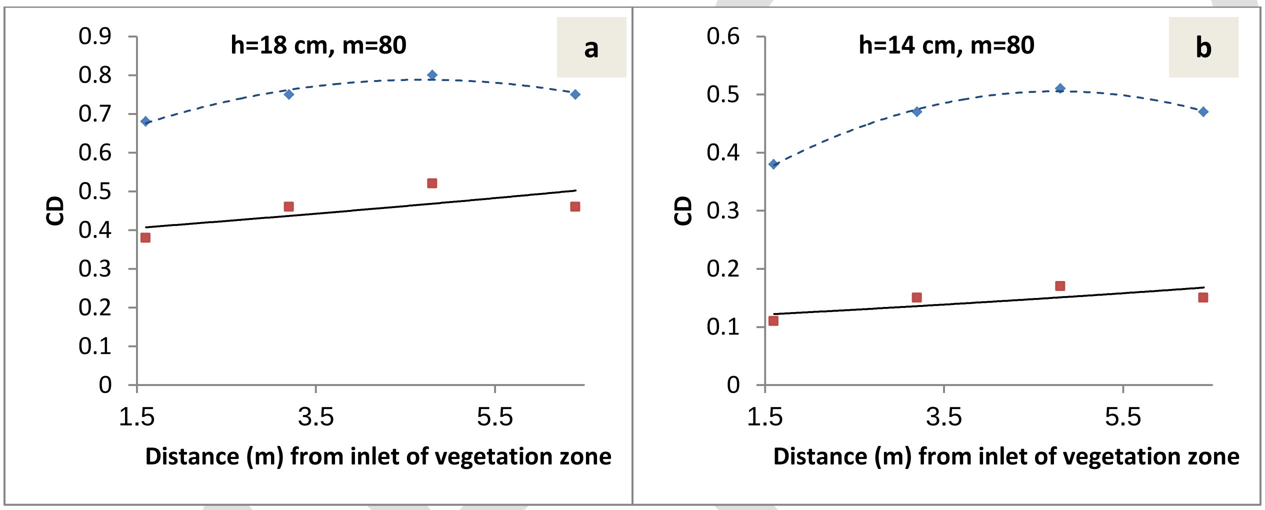


Fig. (4): Difference between Hothoff (2007) and the experimental work for m=80 stem /m^2.

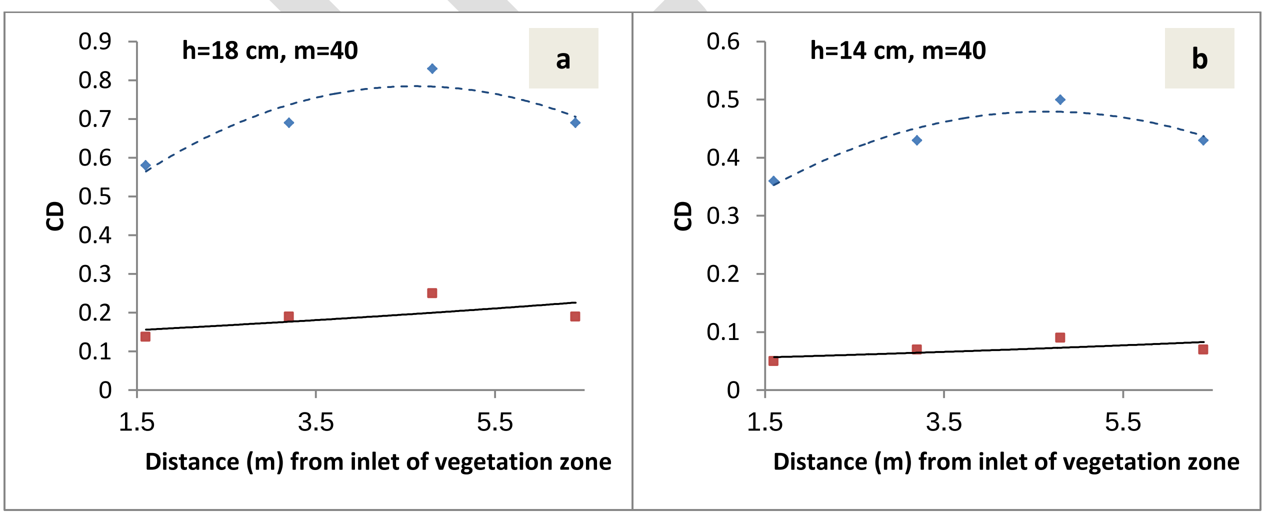


Fig. (5): Difference between Hothoff (2007) and the experimental work for m=40 stem /m^2.

From these figures, it's noticed that, in large water depths, the computed drag values using Hothoff (2007) model were less than the corresponding drag values using the deduced empirical equation from the experimental work because these are more parameters included in Hothoff model and not concluded in the empirical deduced equation.

- ***Effect of flow depth on drag coefficient***

Figures (6a) and (6b) illustrate the effect of flow water depth (h) on the vegetation drag (CD) for m=100 stem /m^2 and 40 stem /m^2. The maximum and minimum vegetation densities were chosen. From these figures, with the increase of water depths (h), drag coefficient values increases, because the corresponding water velocity decreases gradually.

From this figure, it is concluded that, the deduced empirical equation, (equation 20), by modification Baptist et al. (2006) approach gives a very good agreement with Hothoff (2007) approach for submerged case, only at higher vegetation densities (m) and large water depths (h).

In figure (6a) at flow depth of 16 cm for vegetation density of 100 stem/m^2, the computed drag using both Hothoff model and the deduced empirical equation is the same value. This means that the deduced empirical equation number (20) could be modified to give agreement at low depths and lower vegetation densities.

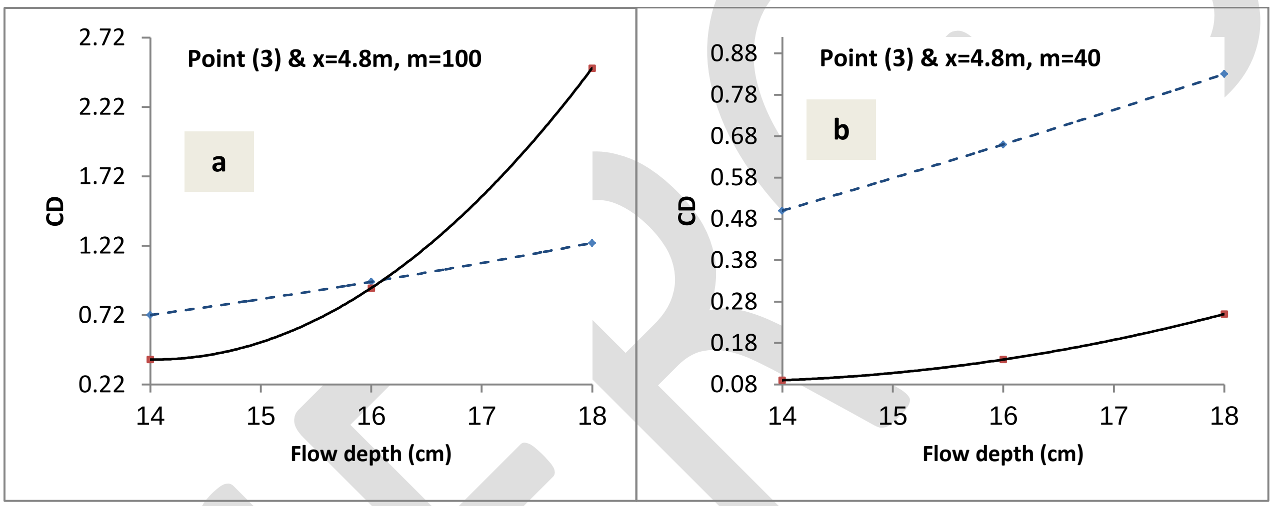


Fig. (6): Effect of flow water depth (h) on the drag coefficient (CD).

The average drag using Hothoff model and the deduced experimental equation for all runs at the three used flow depths is about 0.80 and 1.275 respectively, to give a difference of about 37% between them. So, it is recommended modifying the deduced equation by adding more affecting parameters to minimize this difference.

5. SAMPLES OF THE EXPERIMENTAL RESULTS

Table (1): Experimental data for submerged case at m=100 stem/m^2

<table>
<tr><th colspan="14">Submerged case & m =100 stem/m^2</th></tr>
<tr><td colspan="2" rowspan="2">Point No.</td><td colspan="4">h=18 cm</td><td colspan="4">h= 16 cm</td><td colspan="4">h=14 cm</td></tr>
<tr><td>Cm/sec</td><td>U cm/s</td><td>CD_1</td><td>CD_2</td><td>Cm/sec</td><td>U cm/s</td><td>CD_1</td><td>CD_2</td><td>Cm/sec</td><td>U cm/s</td><td>CD_1</td><td>CD_2</td></tr>
<tr><td rowspan="2">1.0 (x=1.60 m)</td><td>us</td><td>15.21</td><td rowspan="2">14.5</td><td rowspan="2">1.03</td><td rowspan="2">1.37</td><td>16.9</td><td rowspan="2">16.0</td><td rowspan="2">0.73</td><td rowspan="2">0.50</td><td>19.36</td><td rowspan="2">18.0</td><td rowspan="2">0.50</td><td rowspan="2">0.22</td></tr>
<tr><td>u_v</td><td>12.0</td><td>13.2</td><td>14.6</td></tr>
</table>

2.0 (x=3.20 m)	**us**	14.57	13.8	1.13	1.88	14.73	14.2	0.94	0.85	17.0	16.0	0.63	0.32
	u_v	11.1				12.6				13.4			
3.0 (x=4.80 m)	**us**	14.11	13.2	1.24	2.50	14.90	14.00	0.96	0.915	15.89	15.0	0.72	0.40
	u_v	10				11.3				12.8			
4.0 (x=6.40 m)	**us**	15.53	14.50	1.03	1.37	14.86	14.20	0.94	0.85	17.10	16.1	0.63	0.32
	u_v	11.5				12.2				13.6			

Table (2): Experimental data for submerged case at m=80 stem/m^2.

Submerged case & m =80 stem/m^2													
Point No.		**h=18 cm**				**h= 16 cm**				**h=14 cm**			
		Cm/sec	**U** cm/s	**CD_1**	**CD_2**	Cm/sec	**U** cm/s	**CD_1**	**CD_2**	Cm/sec	**U** cm/s	**CD_1**	**CD_2**
1.0 (x=1.60 m)	**us**	20.57	19	0.68	0.38	21.97	21	0.48	0.18	24.68	22	0.38	0.11
	u_v	16.2				17.3				19.44			
2.0 (x=3.20 m)	**us**	19.17	18	0.75	0.46	20.95	19.5	0.56	0.23	22.86	20	0.47	0.15
	u_v	15.1				16.5				18.0			
3.0 (x=4.80 m)	**us**	19.17	17.5	0.80	0.52	19.99	18.9	0.60	0.26	21.72	19.2	0.51	0.17
	u_v	14.2				15.7				17.11			
4.0 (x=6.40 m)	**us**	19.43	18	0.75	0.46	20.73	19.5	0.56	0.23	22.2	20	0.47	0.15
	u_v	15.3				16.33				18.0			

CD_1 = Hothoff (2007) and CD_2 = Experimental deduced equation

Table (3): Experimental data for submerged case at m=40 stem/m^2.

Submerged case & m =40 stem/m^2													
Point No.		**h=18 cm**				**h= 16 cm**				**h=14 cm**			
		Cm/sec	**U** cm/s	**CD_1**	**CD_2**	Cm/sec	**U** cm/s	**CD_1**	**CD_2**	Cm/sec	**U** cm/s	**CD_1**	**CD_2**
	us	26.59				28				31.2			

1.0 (x=1.60 m)	**u_v**	19.7	25	0.58	0.138	22	27	0.45	0.08	24.7	28.5	0.36	0.05
	us	24.2				27.05				28.2			
2.0 (x=3.20 m)	**u_v**	18.8	23	0.69	0.19	21.3	24.5	0.54	0.11	22.2	25.8	0.43	0.07
	us	22.79				24.13				25.53			
3.0 (x=4.80 m)	**u_v**	17.95	21	0.83	0.25	19.0	22.3	0.66	0.14	20.11	24.2	0.50	0.09
	us	24.13				26.67				28.105			
4.0 (x=6.40 m)	**u_v**	19.0	23	0.69	0.19	21.0	23.8	0.58	0.123	22.13	25.8	0.43	0.07

CD_1 = Hothoff (2007) and CD_2 = Experimental deduced equation

6. CONCLUSIONS

In this paper, the submerged vegetation resistance using movable bed surface were studied. Three different densities of linear cylindrical artificial vegetation of were used. According to the condition of Kleinhans (2008), for submerged vegetation case, the used stem height is 4 cm to give h/k (water depth-stem height ratio less than 5 for all used flow depths. Acoustic Doppler Velocimeter (ADV) instrument was used to measure water velocities at the centerline of channel along the vegetation zone.

A comparative study was done between Hothoff (2007) and the experimental results. An empirical equation was deduced using SPSS program and dimensionless method by modification Baptist et al. (2006) approach as:

$$U = \left(\sqrt{\frac{2g}{CD\ K}} + \frac{\sqrt{g}}{K}\ \ln\left(\frac{h}{k}\right) \right) \sqrt{0.7\ h\ i} \qquad (R^2=0.85)$$

Measuring the average vegetation velocity (U_v) and the surface velocity (U_s), Klopstra et al. (1997) model was used to compute the average water depth velocity. The deduced empirical equation gives a very good agreement with Hothoff (2007) approach for submerged case, only at higher vegetation densities (m) and large water depths (h). The average drag value using Hothoff model and the deduced equation is about 0.80 and 1.275 respectively, to give a difference of about 37% between them. So, it is recommended modifying the deduced equation by adding more affecting parameters to minimize this percentage.

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