A laboratory study of gradually varied flow through semi-rigid emergent blade-type vegetation

A.O. Busari and C.W. Li
Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, HKSAR, China

Abstract

Vegetation is an important component of an aquatic ecosystem and contributes to the natural defense of coastal areas from currents, waves and storm surges. This study investigates the hydrodynamics of blade-type vegetation under gradually varied flow. In the laboratory cable tile blades are used to simulate vegetation elements. The blades are fixed to PVC boards of length 2.4m. The spacing of blade elements is different for different boards and the finite artificial vegetation patches are of densities $\lambda = 72, 48, 24, 18, and\ 15$ and blade Reynolds number $Re = 510 - 1220$. Six flow rates are used in each set of experiments. The longitudinal water surface profiles have been measured and the effect of increasing roughness density under the flow conditions examined. A theoretical equation that relates vegetation resistant force and water surface profile (Li and Tam, 2002) has been modified and used for determining the averaged drag coefficient C_d. The results show that C_d varies with the vegetation density with an apparent trend due to the change in the number of shedding eddies per unit area. A better understanding of the resistance mechanism of the geometrical shape of vegetation elements is obtained.

1. Introduction

The understanding of benefits rendered by vegetation such as storm surge protection, habitat for economically important aquatic animals, bank/channel stabilization and water quality improvement. Restoration of plants along channels and coastal areas increases the hydraulic resistance, thereby reducing flow speed and consequently reducing erosion. The viscous and pressure drags on the plants account for the hydraulic resistance of waterways and coastal zones, and cause energy losses. The hydraulic resistance force is proportional to the square of the velocity and a roughness coefficient, the Manning's *n* or the drag coefficient, C_d.

The vegetation induced drag is dependent on many factors such as patchiness, plant mechanical properties, age, seasonality, foliage and vegetation density (e.g., Wu et al., 1999, Stone and Shen, 2002; Tanino and Nepf, 2008, Nikora et al., 2008, Yang and Choi, 2009, Dharmasiri et al, 2012). The drag coefficient, therefore, varies with vegetation parameters, geometry, patterns, degree of flexibility and flow conditions. These conditions are to some extent can be simulated in the laboratory. Owing to the ecological values and flood risk management function of vegetation, the understanding of the vegetated-channel flow behavior is required for better prediction of flow and dispersion phenomena.

The key parameter for the quantification of the flow in vegetated waterways is the drag coefficient. A number of important findings on flow resistance have been obtained from previous studies using the principal assumption that plants are treated as rigid cylinders (i.e., Rigid Cylinder Analogy (RCA) e.g., Nepf, 1999; Ishikawa et al., 2000; James et al., 2004; Liu et al, 2008; Tanino and Nepf, 2008; Ferreira et al., 2009; Kothyari et al., 2009; Stoesser et al., 2010 and Cheng and Nguyen, 2011). More recently, Aberle and Jarvela, (2013) analyzed the parameterization of form drag as well as the estimation of flow resistance for emergent vegetation. They inferred that the key hydraulic property of plants, flexibility, vegetal parameters and geometry is practically better than the well-known RCA since plant characteristics are not adequately portrayed using RCA.

Wu et al., (1999) developed equations for vegetal drag coefficient for submerged and non-submerged vegetation under uniform flow condition using rubberized fibers. They concluded that C_d depends on a vegetative characteristic number which is related to the biomechanical properties of the plants. In fact, various studies suggested different trends for bulk drag coefficient against vegetation density (λ) for cylinder arrays. For example, Nepf (1999) reported a decreasing tendency of C_d with increasing λ, whereas the opposite have been reported in Ishiwaka et al. (2000), Tanino and Nepf (2008), and Stoesser et al. (2010). A low correlation has been found between Re (ub_v/v) and C_d for high density emergent vegetation (Ishiwaka et al, 2000). Recently, Dharmasiri et al, (2012) simulated the flow through non-submerged vegetation using rigid cylinder analogy, by varying the distribution pattern only in the flow direction and concluded that C_d is correlated with vegetation density and follows a quadratic law with maximum C_d corresponding to highest concentration of eddies.

Most studies focused on rigid cylinder with uniform flow through vegetation (e.g., Stone and Shen, 2002: Tanino and Nepf, 2008; Cheng and Nguyen, 2011), Nehal et al., (2012), however, used plastic blades to simulate vegetation and showed that vegetation density is an important variable in the flow resistance model for emergent vegetation. They concluded that the estimation of C_d and λ is paramount for flow resistance model, although, they considers moderate density, uniform flow condition and low discharge which may not be applicable especially during flood events. Li and Tam, (2002) studied simulated semi-rigid vegetation (using black rubber rods) under non-uniform condition with gentle bed-slope of 1:1000. The authors obtained and verified a theoretical equation that relates vegetation resistant force and water surface profile. Using the derived equation, the value of C_d can be determined. The study of semi-rigid blade type vegetation is seldom. In this present study, a laboratory flume study is carried out with vegetation simulated by cable tile blades (considering the advantage of more flexibility with smaller thickness). It is hypothesized that the C_d relation based on momentum balance equation for gradually varied flow proposed by Li and Tam, 2002 can be modified into geometric - average pore velocity variable relation. The modified relation depends on the flow condition and vegetal density. Using the relation, the C_d and hydraulic characteristics of dense emergent blade-type vegetation under non-uniform flow are discussed using the flow interference mechanisms such as channeling effects, shielding effects and eddy concentration. The comparison of the results obtained with existing analytical solution suggested that the head loss is an importance parameter for estimation hydraulic roughness.

2. Theoretical background of experiment

The drag force for each stem blade in stream-wise direction is expressed as (e.g., Kothyari et al., 2009; Cheng and Nguyen, 2011)

$$F_d = 0.5 C_d \rho h b_v u_v{}^2 \qquad (1)$$

where C_d is the drag coefficient; ρ is the fluid density *(kg/m^3)*; h is the water depth (*m*); b_v is the width of stem (*m*); hb_v is the frontal area and u_v (*m/s*) is the average pore velocity approaching the stem. For high-density vegetation, the average pore velocity through vegetation as the characteristic velocity for evaluating stem drag is given by

$$u_v = Q/Bh/(1-\phi) \tag{2}$$

in which B is the channel width (m) and $\phi = Nb_v t_v$ (-) is the average volume fraction occupied by vegetation stem often referred to as area concentration and t_v (m) is the thickness of the blade ~~(m)~~. N is the number of vegetation per unit area (*stem/* m^2). The total drag per unit- bed area can be described by equation 3.

$$\frac{\phi F_d}{b_v t_v} = \frac{C_d \phi \rho h b_v u_v^2}{2 b_v t_v} = \frac{C_d \phi \rho h u_v^2}{2 t_v} \tag{3}$$

2.1. Uniform flow condition

Under steady, uniform flow condition, the drag force is balanced by the streamwise component of the gravitation force, that is

$$\frac{C_d \phi \rho h u_v^2}{2 t_v} = (1-\phi)\rho g h S \tag{4}$$

in which S (-) is the bed-slope, g = acceleration due to gravity (m/s^2). By neglecting the shear forces at the bed and sidewalls, the drag coefficient for uniform flow condition from equation (4) is given by

$$C_d = 2\mathrm{gS}\,\frac{(1-\phi)}{\phi u_v^2}\,t_v \tag{5}$$

The drag coefficient for blade elements can be formulated in terms of vegetation-related hydraulic radius (h_r). Considering a vegetation zone of length, L (m); the h_r is defined as the ratio of cross-section area to effective wetted perimeter.

$$h_r = (1-\phi)BhL/\psi h b_v$$

where ψ=*NBL* is the numbers of stems.

$$h_r = \frac{(1-\phi)BhL}{NBLhb_v} = \frac{(1-\phi)}{Nb_v} == \frac{(1-\phi)t_v}{\phi} \tag{6}$$

Comparing equations (5) and (6), the drag coefficient is given by

$$C_d = 2\mathrm{g}\frac{h_r}{u_v^2}S \tag{7}$$

2.2. Gradually varied flow condition

The total drag force on emergent blade-type vegetation in a fluid volume of unit length can be defined as

$$NBF_d = 0.5\lambda C_d \rho h B u_v^2 \tag{8}$$

where $\lambda = Nb_v$ is the vegetation density (m^{-1})

The movement of fluid through vegetation generates drag which creates velocity gradients and eddies that result in losses of momentum. These losses are very important for a wide range of flow conditions which has not be fully considered in the prediction of flow resistance. In dense vegetated waterways (such as that simulated in Figure 1), the effect of vegetative drag on the velocity is significant as well as on the water surface elevation. Under this condition, the expression for C_d estimation should consider the effect of significant variation of water surface elevation in vegetated channel.

Figure 1: A sectional plan view of the dense vegetation ($= 0.1214$ array)

In this analysis, vegetation is taken to be the only source of energy dissipation along the waterway. For an open channel flow through emergent vegetation, over a small longitudinal distance, Δx, a decline in the hydraulic head, Δh is ~~required~~ resulted. By applying the principle of conservation of momentum, Li and Tam, (2002) simplified the momentum balance equation as follows

$$\left(\lambda C_d hB\rho \frac{u^2}{2} - \rho g BhS\right)\Delta x = -\left(\rho g Bh - \frac{\rho Q^2}{Bh^2}\right)\Delta h \tag{9}$$

where Q = flow rate (m^3/s). The first, second, third and fourth terms in equation (9) represent the drag force, body force, pressure force and the rate of change of momentum flow rate respectively.

The use of average flow velocity, u only applies to low density vegetation. For dense vegetation, the average velocity is replaced by the average pore velocity. Substituting equation (2) into equation (9) yields:

$$\left(\lambda C_d \rho Bh \frac{u^2}{2(1-\phi)^2} - \rho g BhS\right)\Delta x = -\left(\rho g Bh - \frac{\rho Q^2}{Bh^2}\right)\Delta h \tag{10}$$

Defining u in terms of flow rate and integrating equation (11) between the limits of initial flow depth, h_o to h with respect to distance x gives the following expression.

$$F(h) = -\int_{h_o}^{h} \frac{ghB - \frac{Q^2}{Bh^2}}{\frac{\lambda}{2} C_d \frac{Q^2}{Bh(1-\phi)^2} - gBhS}\, dh = x + \text{constant} \tag{11}$$

From the measured water surface profile (h against x) for different flow rate of varying vegetation density, $F(h)$ in equation (11) can be evaluated numerically by assuming a value of drag coefficient. Using trial and errors method, a straight line of unit slope obtained from the plot of $F(h)$ against x is an indicator that the value of C_d has been chosen correctly.

3. Experimental techniques

The laboratory experiments were conducted in a 0.31 m wide, 0.40 m deep and 12.50 m long tilting and slope – adjustable rectangular flume to verify the theoretical expression. The sidewalls and bottom are made of glass and steel respectively. Flow rates were measured by an electromagnetic flowmeter installed in the flow return pipe. The longitudinal bed-slope of the flume can be varied from -0.83 to 2.0%. The flow at the entrance of the channel was straightened using a series of honeycomb grids, thereby preventing the formation of large-scale flow disturbances. The flume received a constant supply of water from a head tank with adjustable tailgate at the downstream end of the flume to regulate the flow depth. Water leaving the flume entered a large sump under the flume, where it was recirculated to the constant head tank with a pump. Two wheeled trolleys, which can be moved along the double-rail track on the top of the flume, were used to mount the point gauge and the channel surface slope was calculated from the longitudinal flow-depth variation, which was measured with a Vernier point gauge with ± 0.1 mm accuracy.

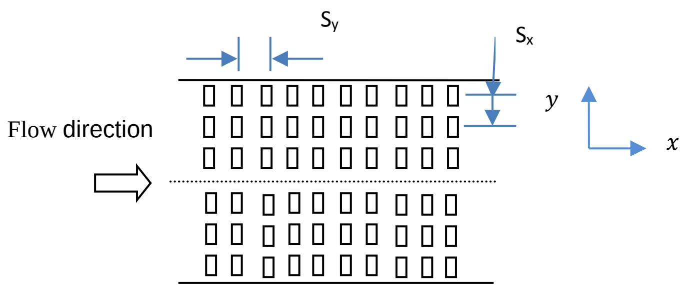

Figure 2: Vegetation pattern

Along the flume was the vegetation patch length of 2.4m long and 0.3 m wide, which was simulated with arrays of semi-rigid cable tile blades. The spacing of blade elements is different for different boards (see Figure 2) and is shown in Table 1. The finite artificial vegetation patches are of densities, $\lambda = 72, 48, 24, 18, and\ 15$. The cable tile blades are of 0.25m height, 0.00753m width and thickness, t_v of 0.00168m ~~by geometry~~ and were fixed to on a PVC board along the channel (as shown in Figure 3) with a fixed bed-slope of 1.67%.

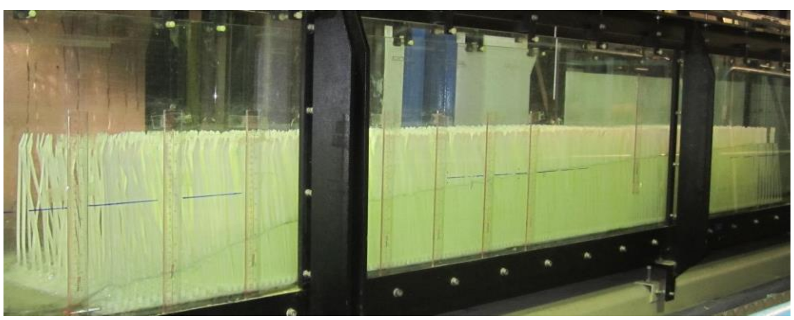

Figure 3: Emergent vegetation simulated with semi-rigid cable tile blade

Table 1 summarizes hydraulic condition and vegetation model for the run of 30 experiments. Six flow rates are used in each set of density and partial submerged results are excluded. For each run, the flow depth was measured at 5cm interval along the vegetation patch length. The values of velocity were calculated from the measured flow discharges using equation (2).

Table 1: Experimental conditions

Q (m^3/s)	h_{av} (m)	u (m/s)	Re (-)	Fr (-)	Allocation patterns of vegetation elements (m)
0.0014 - 0.0083	0.061- 0.228	0.083 - 0.134	627 - 1008	0.089 - 0.107	Sx = 0.0125; Sy = 0.0083
0.0014 - 0.0056	0.073 - 0.197	0.067 – 0.099	507 - 744	0.071 - 0.080	Sx = 0.0125; Sy = 0.0125

0.0014 - 0.0056	0.068 - 0.176	0.0684-0.106	515 - 798	0.081 - 0.084	Sx = 0.0125; Sy = 0.025
0.0014 - 0.0069	0.048 - 0.157	0.0970 - 0.147	731 - 1108	0.119 - 0.1418	Sx = 0.020; Sy = 0.020
0.0014 - 0.0083	0.046 - 0.171	0.099 - 0.162	747 - 1218	0.125 - 0.147	Sx = 0.020; Sy = 0.025

4. Results and discussion

4.1 Experimental and theoretical water surface profile

The experimental results of some of the water surface elevations for different densities and flow rates are presented in Figure (4). A good agreement between the measured and theoretical results indicates the correctness of the assumed C_d values. Generally, the water level increase with increase in vegetation density under the same flow rate. The blades impede the water flow create head losses. A sharp hydraulic gradient resulting in high head losses has been observed for λ value of 24 m^{-1} regardless of the flow rate. This is due to the increase in concentration of eddies resulting from wide separation of blades across stream-wise direction (S_y) thereby compensating the shielding effects on blades. The velocity of water flowing through the narrow gaps along the streamwise direction is, also reduced due the high pressure drag on the blades. For higher discharges, the fluctuating of water force in the flume becomes larger due turbulence.

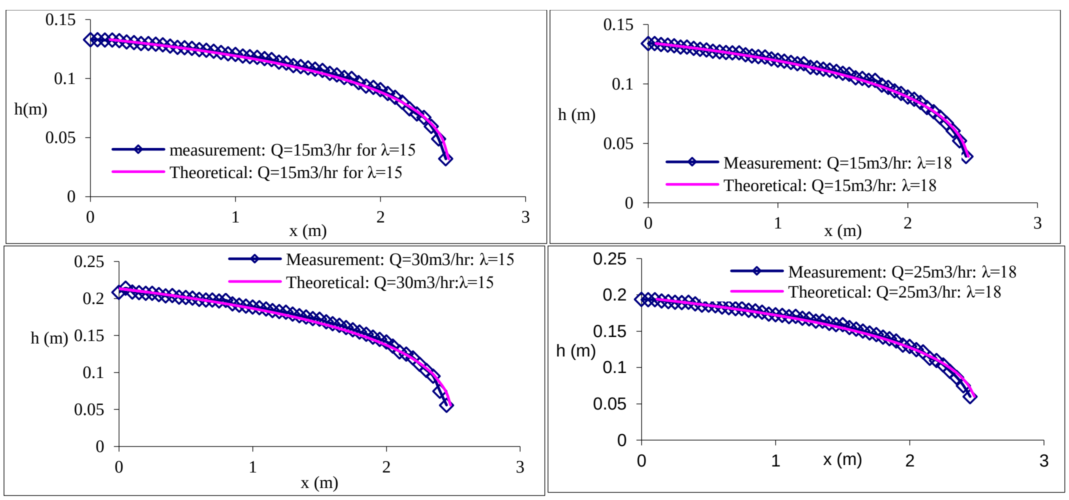

Figure 4: Water surface profiles for flow semi-rigid vegetation (Comparison of experimental and theoretical results)

The major interference mechanisms include the flow channeling and sheltering effects, as well as the shedding of eddies and wake formation. The interference effects can be observed when water flow through the narrow blade gaps at high velocity, thereby lowering the pressure on the blades (sheltering effect). The low pressure and the single-wake behaviour of flow over array of blades provide explanations for the observed interference effects as shown in figure (5).

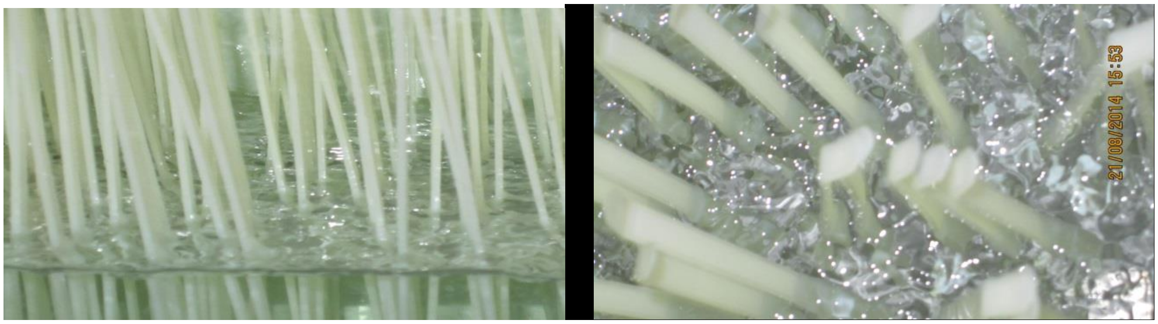

Figure 5: Interference effects on blades (*a*) side view; (*b*) top view

4.2 Dependence of drag coefficient on blade Reynolds number and vegetation density

The drag coefficient obtained from a good fit of theoretical model (equation 11) with experimental results as discussed in section (4.1) showed more or less a linear dependence on the blade Reynolds number. Generally, the vegetation pattern as shown in Figure (2) allows wake interference between blades. Figure (6*a*) showed that the drag coefficient, C_d decrease with increasing blade Re (for $\text{Re} \leq 1220$). The exception is the case of the highest density ($\lambda = 72\ m^{-1}$) in which C_d appears to slightly increase with Re, and the value of Cd is the smallest due to the suppression of eddies shedding as a result of the close separation among blades. The low value of C_d can also be explained by the velocity reduction in the wake region. C_d slightly increases with ~~i~~ flow rates, becomes nearly constant and suddenly decreased due to turbulence.

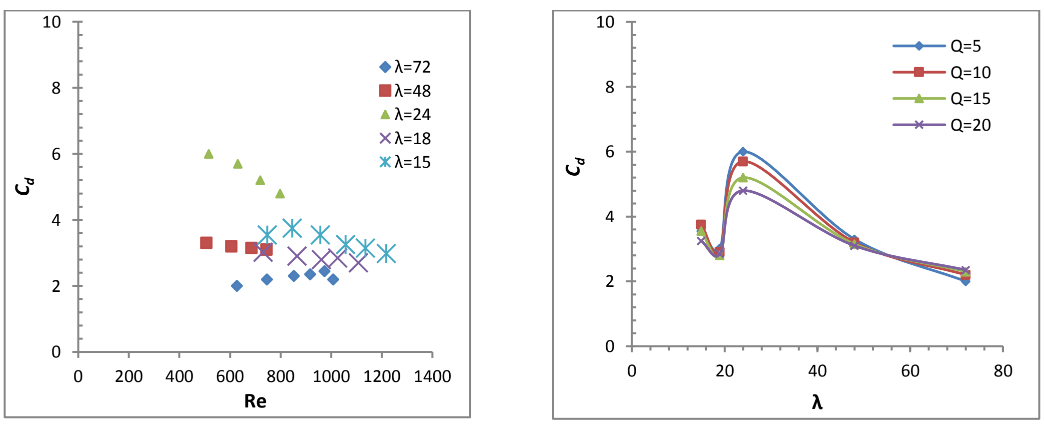

Figure 6: Bulk drag coefficient, (*a*) function of Reynolds number and (*b*) vegetation density

In Figure (6b), by varying the density of distribution, C_d increases with λ, attaining a maximum value corresponding to the largest shedding of eddies (λ = 24) and then start to decrease with λ. Further variation of distribution gaps along the flow direction showed possible increase in C_d due to the increasing number of shedding eddies per area (?). The observed trend implies that other interference effects may affect the drag. Generally, the shielding effect is significant for high density due the destruction of eddies shedding owing to the concentration of blades while channeling effect dominates in low density cases. Increase in flow rate for different vegetation densities has been observed to lower the maximum point considerably due to high velocity of flow through the blade gaps as well as turbulence buffeting contributed by the wake.

4.3 Force on emergent blade and area density

In Figure 7, the vegetal drag force parameter (u^2C_d) for emergent blade is measured as a product of estimated drag coefficient and square of flow velocity. The drag force is strongly correlated to the vegetal area concentration, and follows a power law relationship. The exponent is dependent on the vegetal area concentration and flow condition. It has been observed that C_d decreases with increase in average pore velocity. The drag force parameter decrease with increasing ϕ due to low pressure drag on the blades (shielding effects). Increasing flow rates causes the increase in turbulence and forces more water to flow along the separation between blades (channeling effects) which in turns amplifies the vibration of the blades.

4.4 Comparison of results with analytical solution

In dense vegetated waterways (such as simulated in this study), the effect of vegetative drag on the velocity is significant as well as on water surface elevation. In comparison, the drag coefficient was computed using the approach by Stone and Shen (2002). For emergent case, (equation 11, Stone and Shen, 2002) can be simplified as follows

$$0.5u_c^2 C_d l^* N b_v = ghS(1 - \phi l^*) \; (l^* \cong 1)$$

$$u_c^2 C_d = 2gS(1 - \phi)/Nb_v \tag{13}$$

where $u_c = u_v/(1 - b_v\sqrt{N})$ and it is referred to as the average velocity in stem layer at constricted section.

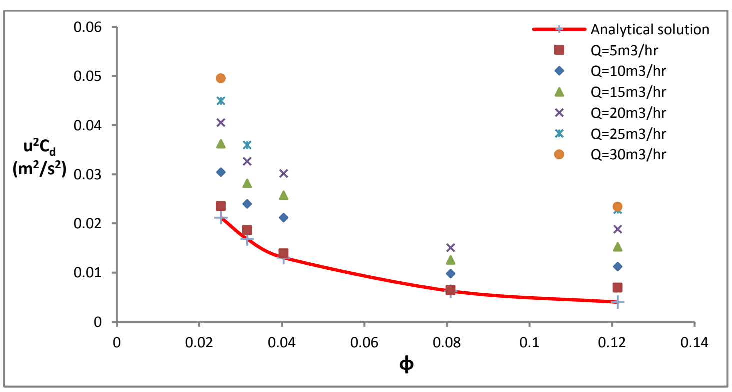

Figure 7: Effect of flow rate on vegetal drag force parameter and blade volume fraction

The variation of flow force parameter $u_c^2 C_d$ against vegetation area density for different flow rates is included in Figure 7. A comparison is drawn between computed resistance parameter (equation 13) and the measured one, although equation 13 was derived under steady and uniform flow condition. The C_d calculation based on equation 13 or the approach by Stone and Shen grossly under predict C_d and the resistance force, due to the inaccurate estimation of the interference effects of dense blade arrays. The predictions become worse with increasing flow rate.

5. Conclusions

Laboratory experiments were conducted to investigate the hydraulic behaviour of semi-rigid blade type vegetation under subcritical gradual varied flow conditions. A modified theoretical equation that relates vegetation resistant force and water surface profile has been verified against experimental data. Based on this equation, the averaged values of the drag coefficient C_d were obtained. The results show that when the distribution pattern of vegetation arrays is changed both along and across stream-wise directions, the interference effects can be significant. The C_d increases with blade density reaching a peak value corresponding to the largest concentration of eddies and then start to decrease with increasing λ. Possibility of increase in C_d due to increasing shedding eddies per area has been noticed with further increase in distribution gaps along the flow direction, however, the effect on C_d is less significant due to channeling effect. Generally, the interference (shielding) effect is substantial for high density. Finally, the effects of interference were highlighted by comparing experimental results with the semi-analytical equation.

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