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Prediction of Flow Velocity Profiles of Open-Channels with Submerged Vegetation

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ABSTRACT

For submerged vegetated flow, the vertical velocity profile can often be described by two layers, the vegetation layer in the lower region and the surface layer in the upper non-vegetated region. In this paper, based on the momentum equation of flow with an assumption of turbulent eddy viscosity being a linear relationship with the local velocity, a two-layer velocity profile for flow in an open-channel with rigid submerged vegetation is proposed. The proposed model was tested against several datasets widely used previously in literature. Our studies show that the model can predict the velocity profiles well for all datasets. In the test, it was found that the mixing length scale of eddies (λ) is well related with both vegetation height (h) and flow depth of surface layer (i.e. height of non-vegetation layer, H-h). Close examination of the length scale λ in the proposed model showed that when λ/h = 0.03(H/h-1)$^{1/2}$, the model can predict velocity profiles well for all the datasets used. The datasets used include various submergence [flow depth (H)/vegetation height (h) =1.25 ~ 3.33], different vegetation densities of a =1.1 ~ 18.5 m^{-1} (a defined as the frontal area of the vegetation per unit volume) and bed slopes ($S_o = 4.0\text{x}10^{-4} \sim 4.0\text{x}10^{-3}$).

KEY WORDS: Velocity profile; Vegetated flow; Sub-merged vegetation; Analytical model; Open-channel flow; Analytical model.

INTRODUCTION

Vegetation exists in many natural rivers and wetlands. The presence of vegetation retards flow by exerting drag force on the flow, consequently influencing the flow field; as a result the vegetation will increase flow resistance or reduce the conveyance capacity of rivers and alter the vertical velocity profile. In certain circumstances, vegetation has to be removed from open channels (Nepf and Ghisalberti, 2008). Nevertheless, flow retarding effect of vegetation reduces bed shear stresses so that the presence of vegetation will reduce bed erosion and produce sedimentation (Lopez and Garcia, 1998). Therefore, vegetation could be beneficial in river restoration works and aquatic life protection by reducing water turbidity and stabilizing river banks (Liu et al., 2008). The impact of vegetation on the vertical velocity profile depends on the type of vegetation (rigid or flexible) and whether the vegetation is emergent or submerged. As a pre-requisite for the analysis of flow resistance, pollutant mixing process, and so on, the velocity profile in an open-channel with vegetation has drawn the attention of many researchers (e.g. Tsujimoto & Kitamur 1990, Shimizu & Tsujimoto, 1994; Klopstra et al., 1997; Meijer & Van Velzen, 1999; Nepf & Koch, 1999; Nepf & Vivoni, 2000; Lopez & Carcia, 2001; Gahisalberti & Nepf, 2004; Defina & Bixio, 2005; Baptist et al., 2007; Kubrak, et al. 2008; Huai, et al. 2009; Yang & Choi, 2010; Dimitris & Panayotis, 2011; Nepf, 2012; Nguyen , 2012; Tang & Ali, 2013; Hao et al. 2014). However, due to differences in flow conditions and vegetation types, various analytical methods for predicting the velocity profile have been proposed based on a 1D streamwise momentum equation of vegetated flow. Recently, Tang and Ali (2013) reviewed recent studies on velocity profile prediction of one-dimensional flow through submerged rigid vegetation and showed that two different analyses are used to determine velocity profile through and above submerged vegetation. The most commonly used approach is a two-layer or three-layer approach for predicting the velocity profile of the flow with submerged vegetation, in which different analytical models are applied in the lower vegetation layer and the upper surface layer, based on an eddy mixing-layer analogy (Klopstra et al., 1997; Meijer & Van Velzen, 1999; Gahisalberti & Nepf, 2004; Defina & Bixio, 2005; Baptist, et al., 2007; Huai, et al. 2009; Yang & Choi, 2010; Nepf, 2012).

For example, Klopstra et al. (1997) proposed a two-layer model for predicting the velocity profile through and above submerged rigid vegetation by dividing the flow field into two layers, one within vegetation and one above it called the surface layer. In the vegetation layer, based on the analogy of turbulent shear stress, the turbulent eddy viscosity is described by the product of a characteristic length (λ) and the local velocity (u), where λ is related to H/h (H is the flow depth and h is the height of vegetation) via an empirical formula, which was found by fitting limited experimental data. Afterwards, Meijer & Van Velzen (1999) further studied this model and recommended that λ was approximated as $0.0144\sqrt{Hh}$ after examining more data. Similarly, Defina & Bixion (2005) and Baptist et al. (2007) established their analytical solutions of velocity in the vegetation layer in different forms with λ being given corresponding expressions, as given by $0.0144\sqrt{Hh}$ and 0.05(H-h) respectively. After comparing the models above against a wide range of data, Tang & Ali (2013) showed that the models are capable of predicting the velocity profile reasonably well to certain data, and they have different results, which are not surprising because they used different constants in their models of λ. Moreover, none of these models can predict well against a wide range of data (Tang & Ali, 2013). Meanwhile, Nepf (2012) proposed a model based on different equations, which have some empirical parameters used.

Although the abovementioned analytical models have the capability of predicting the velocity profile, the range of their application is limited, which may be due to the limitation of their proposed parameter (λ). In the present paper, based on the mixing length concept of turbulent eddy, we proposed a two-layer model for predicting the velocity profile of flow with submerged rigid vegetation, with the mixing length (λ) related to both the height of vegetation and the flow depth above the vegetation, i.e. $\lambda = k\sqrt{(H\text{-}h)h}$, where k is a constant. A wide range of experimental data was used to evaluate the proposed analytical model, and it was found that the model when k = 0.03 agrees well with the data by Dunn et al. (1996), Meijer & Van Velzen (1999), Nguyen (2012) and Hao et al. (2014). The test datasets cover different submergence (H/h) ranging from 1.25 to 3.33, various vegetation densities (a =1.1~18.5 m^{-1}) and bed slopes (S_o = 4x10^{-4} ~4x10^{-3}).

MODEL DEVELOPMENT

Based on the momentum equation of steady uniform flow, for the channel flow with vegetation, the bed and wall boundary stress are both assumed to be negligible compared with the drag force on the vegetation, the governing equation for fully-developed 1-D vegetated flow may be described by

$$\frac{1}{\rho}\frac{\partial \tau(z)}{\partial z} = F_v - gS_o \qquad (1)$$

where τ is the shear stress, g the gravity, z the vertical coordinate above the bed, S_o the bed slope, and F_v is the drag force per unit mass generated by the vegetation (see Figure 1). The drag force F_v is given by:

$$F_v = \begin{cases} \frac{1}{2} C_D a\, u^2, & z \le h \\ 0, & z > h \end{cases} \quad ; \quad a = mA_v \qquad (2)$$

where u is the streamwise time-averaged velocity, h the height of vegetation, C_D the drag coefficient, a the density of vegetation, i.e. the frontal area of vegetation (A_v) per unit volume, and m is the number of vegetation per unit area.

The turbulent shear stress (τ) is described by Boussinesq hypothesis through a mixing length concept as:

$$\tau(z) = \rho \nu_T \frac{\partial u}{\partial z} = \rho \lambda u \frac{\partial u}{\partial z} \qquad (3)$$

where ν_T is the total eddy viscosity of vegetated flow, and λ is a mixing length of eddy.

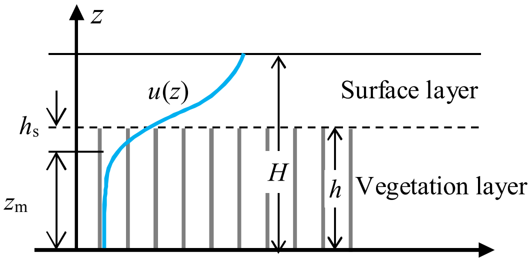


Figure 1. Velocity profile in a channel with sub-merged vegetation

Under steady flow conditions, inserting Eqs. (2) and (3) into (1) gives:

$$\lambda \frac{\partial^2 (u^2)}{\partial z^2} - C_D a\, u^2 + 2gS_o = 0 \qquad (4)$$

For given vegetation density (a) and drag coefficient (C_D), an analytical solution for u^2 in Eq. (4) can be obtained with appropriate boundary conditions (e.g. Klopstra et al., 1997; Defina & Bixio, 2005). The boundary conditions are considered as follows:
At the bed (z=0), where the bed shear stress is neglected, the local equilibrium between gravity force and vegetation drag gives:

$$u_o = u|_{z=0} = \sqrt{\frac{2gS_o}{aC_D}} \qquad (5)$$

At the top of the vegetation (z=h), the boundary shear stress is given by:

$$\tau(z = h) = \rho g(H - h)S_o \qquad (6)$$

It follows the solution of u can be described by:

For the vegetation layer:

$$u = \sqrt{\frac{2gS_o h^2}{\lambda\eta}\left\{\left(\frac{H}{h} - 1\right)\frac{\sinh\left[\eta\left(\frac{z}{h}\right)\right]}{\cosh(\eta)} + \frac{1}{\eta}\right\}} \quad ; \quad \eta = h\sqrt{\frac{aC_D}{\lambda}} \qquad (7)$$

where λ is recommended to be related to both H-h and h, and in this study it is assumed as $k\sqrt{(H\text{-}h)h}$, wherer k is a constant.

For the surface layer, the velocity is described by the well-known logarithmic profile:

$$u = \frac{u_*}{\kappa}\ln\left(\frac{z - z_m}{z_o}\right) = \frac{u_*}{\kappa}\ln\left[\frac{z - (h - h_s)}{z_o}\right] \qquad (8)$$

in which κ is von Karman's constant, z_m (= h – h_s) is the zero-plane displacement of the logarithmic profile, h_s is the distance between the top of vegetation and the virtual bed of the surface layer (see Figure 1), z_o is the equivalent bed roughness height, and u_* is the shear velocity, given by $u_* = \sqrt{gS_o(H - h)}$ and where h_s and z_o are described respectively as:

$$h_s = \frac{gS_o + \sqrt{(gS_o)^2 + 4(\kappa \partial u/\partial z|_{z=h})^2 gS_o(H - h)}}{2(\kappa \partial u/\partial z|_{z=h})^2} \qquad (9)$$

$$z_o = h_s e^{-\kappa\left(\frac{u|_{z=h}}{u_*}\right)} \qquad (10)$$

DATA USED IN STUDY

To test the proposed model described above, we used a wide range of different experimental data for submerged rigid vegetation from the literature. A total of 13 datasets used covers various submergence (H/h), which is 1.25 ~ 3.33, the vegetation densities a =1.1~ 18.5 m^{-1}, and bed slope S_o is from 4x10^{-4} to 4x10^{-3}. The details of the datasets are given in Table 1, where the data of Nguyen (2012) cover different vegetation densities and various diameter sizes of vegetation. The values of C_D in the dataset of emergent vegetation were taken from the original papers if available or assumed if not. It should be mentioned that all the data were from the tests in laboratory flumes.

Table 1. The dataset used for evaluating the models of submerged rigid vegetation

Author	Run	H (m)	h (m)	H/h	a (m^{-1})	C_D	S_o	ah
Dunn et al. (1996)	8	0.391	0.1175	3.33	2.46	1.13	0.0036	0.289
	9	0.214	0.1175	1.82	2.46	1.13	0.0036	0.289
Meijer et al. (1999)	22	2.08	0.90	2.31	2.048	0.97	0.00138	1.843
	34	0.99	0.45	2.20	2.048	0.97	0.0016	0.922
	36	1.50	0.45	3.33	2.048	0.97	0.0014	0.922
Nguyen (2012)	A60-15	0.15	0.10	1.5	1.78	1.13	0.004	0.178
	A30-15	0.15	0.10	1.5	7.11	1.13	0.004	0.711
	B60-15	0.15	0.10	1.5	3.67	1.13	0.004	0.367
	B30-15	0.15	0.10	1.5	14.67	1.13	0.004	1.467
	C60-15	0.15	0.10	1.5	4.61	1.13	0.004	0.461
	C30-15	0.15	0.10	1.5	18.44	1.13	0.004	1.844
Hao et al. (2014)	Test 1	0.10	0.08	1.25	1.355	1.13	0.0035	0.108
	Test 2	0.11	0.08	1.38	1.355	1.13	0.004	0.108

RESULTS AND DISCUSSION

As shown in Section 2, the characteristic length λ reflects the mixing strength of eddy in vegetated flow, and it is closely related to both the flow depth and vegetation height, as recommended as $k\sqrt{(H\text{-}h)h}$ in this study. The larger k value, the smaller λ becomes, i.e. the stronger the eddy, so this indicates a larger velocity, as demonstrated in Fig. 2 as an example. Fig. 2 shows that the prediction of velocity is less sensitive to the value of k used in the model in the vegetation layer, particularly close to the channel bed, but the k value has much large influence on the predictive velocity in the surface region.

As the depth of penetration of turbulent flow is limited, k value should have a certain value within a limited range. After careful examination on k values in the proposed λ model, we found that the value of k =0.03 in the proposed analytical model of u can produce the predictive velocity profiles that generally have good agreement with all the experimental data tested, as shown in Figs. 3-4 for the cases of the submergence of H/h >= 1.5, and in Figure 5 for the case of Nguyen (2012) where the density of vegetation (a) is not very high (e.g. ah < 1.8). Fig. 5 shows that if the density of vegetation is very high, e.g. ah > 1.8, it appears that the velocity predicted by the model is over-estimated in both layers, which indicates the stronger mixing of eddy due to large density of vegetation. In this case, a larger value of k (i.e. larger mixing length λ) is needed.

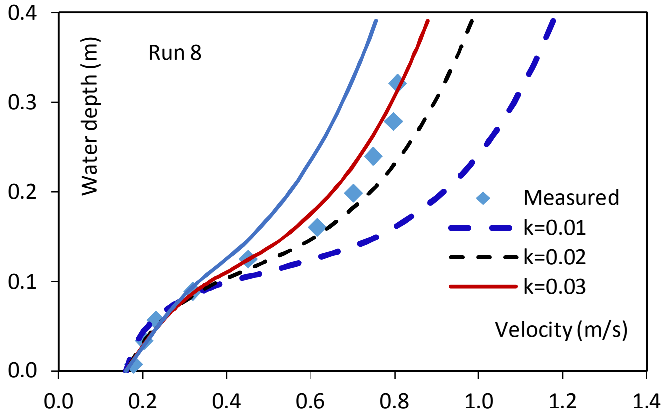


Figure 2. The impact of k value on the model prediction of velocity profile for the data of Dunn et al. (1996).

For the case of shallow submergence as H/h < 1.5 defined by Nepf (2012), e.g. Hao et al. data, the predicted velocity by the model is under-estimated, see Fig. 6. In this case, the value of ah, which represents a dimensionless parameter of vegetation density, is close to the limit value (0.1) recommended by Nepf (2012), who concluded that more care should be paid for any predictive model. This statement appears true to this model.

Further examination of the measured velocity profiles in the vegetation layer shows that the velocity starts to increase exponentially or linearly from distances very close to the channel bed, because in such a region the flow is driven by the turbulent stress and pressure gradient with the balancing force of the vegetation drag, and thus this may be evidence of deep penetration by the turbulent stresses. In this case, the dispersive stress might have become more important because the flow field in the vegetation zone is expected to become relatively more turbulent due to a deep penetration of the turbulent stresses.

Finally, it should be noted that when the mixing length λ is recommended as $0.03\sqrt{(H\text{-}h)h}$, the predicted velocity profile by the model shows good agreement with a range of the data tested. However, further study is needed to evaluate the value of constant k =0.03 for even a wide range of data in the future.

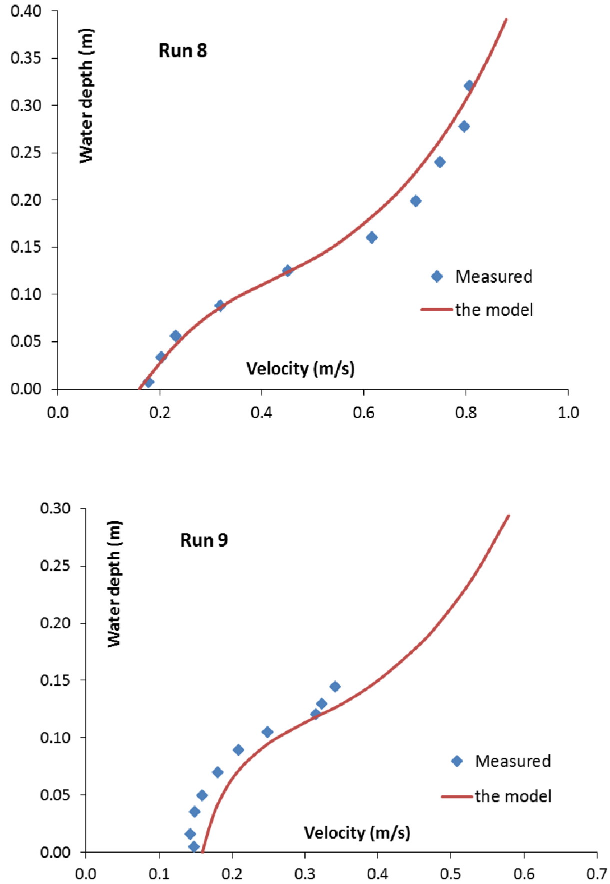


Figure 3. Prediction of velocity profile for the data by Dunn et al. (1996).

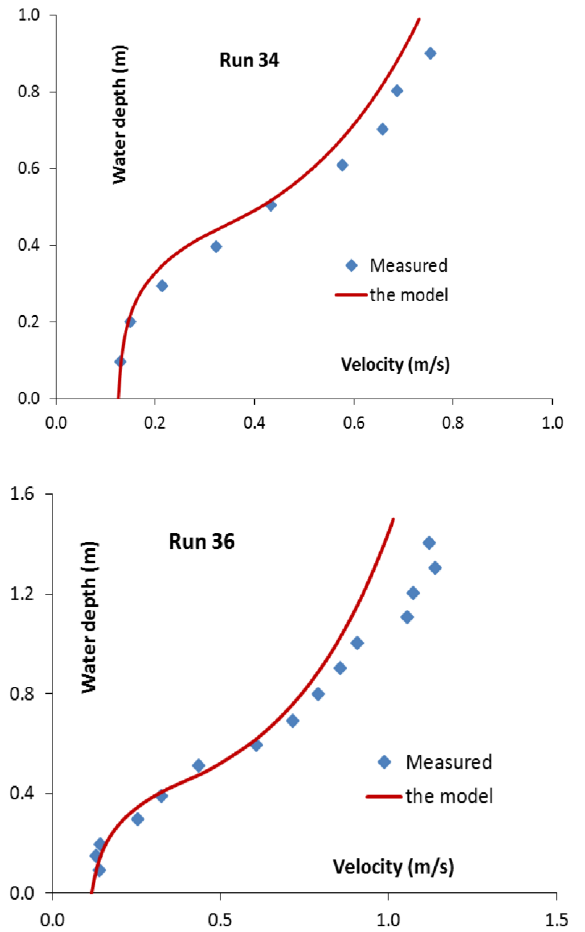
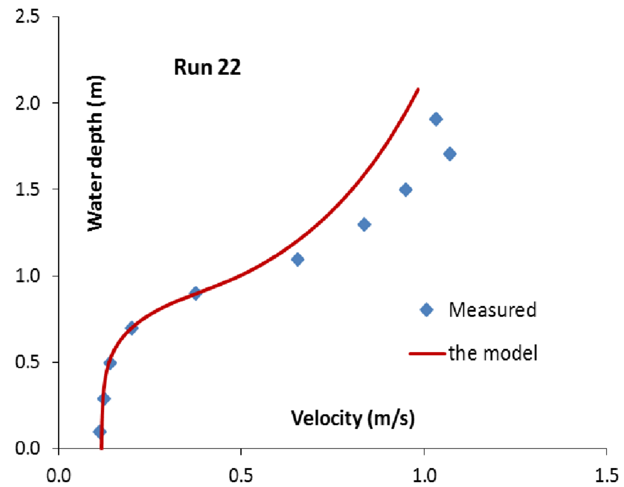
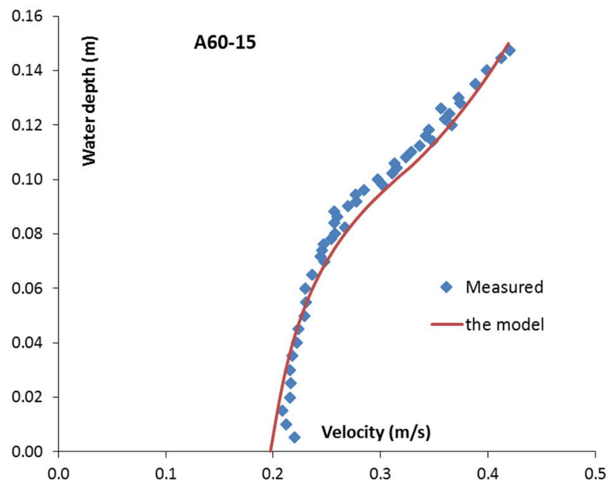
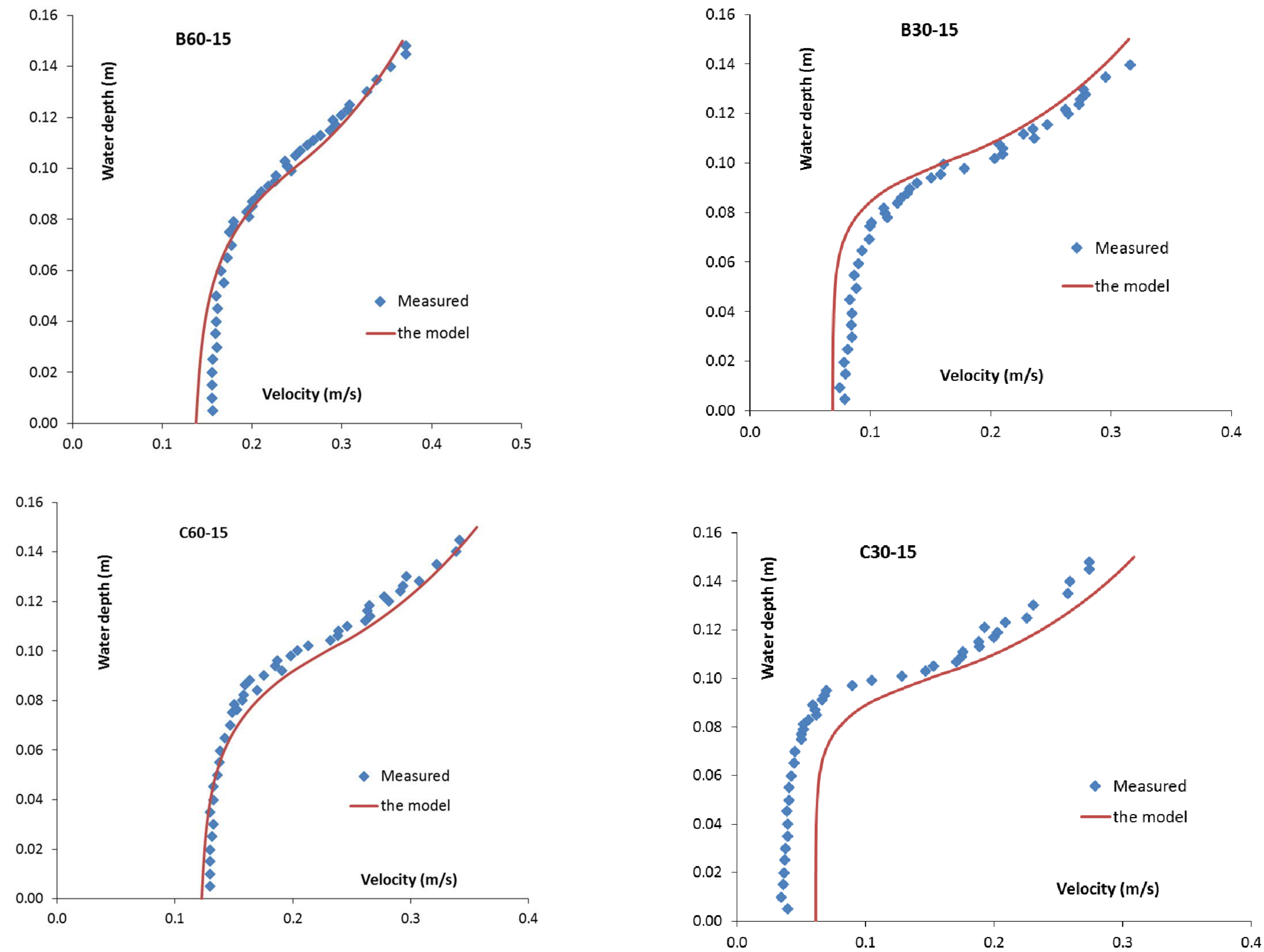


Figure 4. Prediction of velocity profile for the data by Meijer et al. (1999).







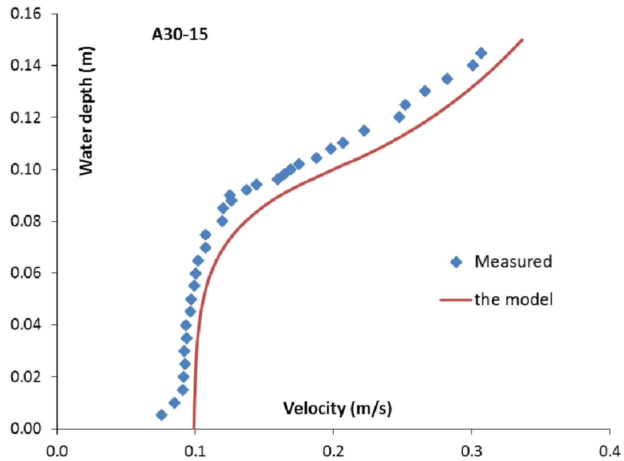


Figure 5. Prediction of velocity profile for the data by Nguyen (2002).

CONCLUSIONS

The presence of vegetation affects the velocity profile of flow. Within submerged vegetation, the vertical velocity profile in the vegetation region is significantly different from that in the non-vegetation surface region. Based on streamwise 1D momentum equation of flow under the assumption of Boussinesq hypothesis by the mixing length concept, an analytical solution of velocity is obtained as given by Equations (7) and (8), which describe the velocity profile in the vegetation region and the non-vegetation region, respectively. Through test against a range of experimental datasets, it was found that the proposed model can predict the velocity well against the data for the cases of non-shallow submergence (H/h>=1.5) when the mixing length can be described by $k\sqrt{(H\text{-}h)h}$ with k having the optimal value of 0.03. However, much care is needed for the cases of shallow submergence (H/h < 1.5), particularly where *ah* (non-dimensional parameter of vegetation density) is close to the limit value 0.1, and this result agrees with the conclusion drawn by Nepf. (2012).

Through a range of data tested against the proposed model, the optimum *k* value of 0.03 is recommended for the proposed λ formula in the proposed model of velocity profile, which shows good velocity profile prediction. It is worth noting that more data in the future can be helpful to establish the recommended value of *k*.

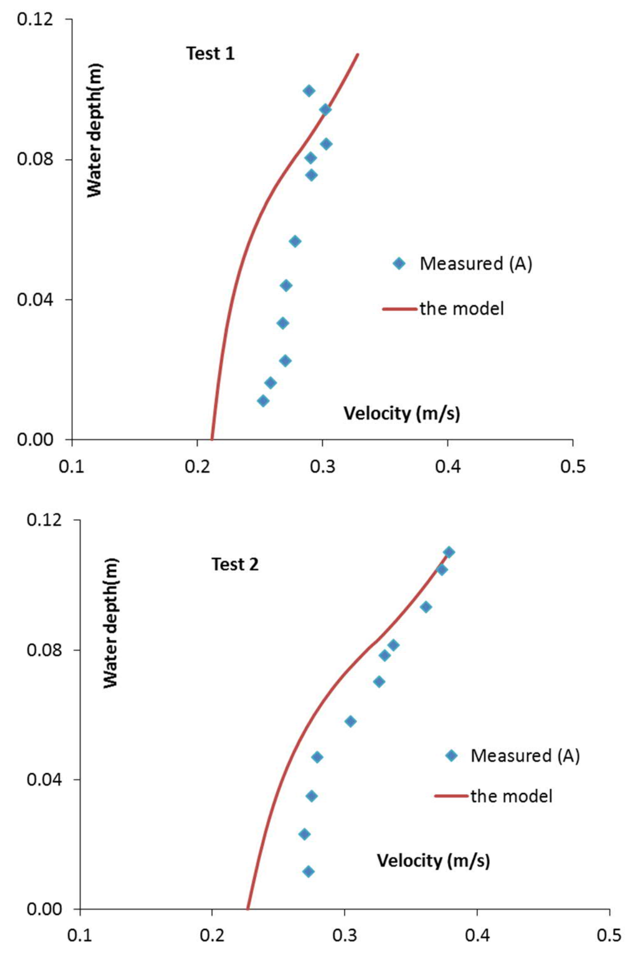


Figure 6. Prediction of velocity profile for the experimental data by Hao et al (2014).

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