ARTICLE IN PRESS

Ecological Indicators xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

Modeling streamwise velocity and boundary shear stress of vegetation-covered flow

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ARTICLE INFO

Keywords:
Vegetation-covered flow
Velocity distribution
Two-power law expression
Asymmetric flow
Shear stress

ABSTRACT

Suspended vegetation floating in open channel alters the flow structure and generates vertically asymmetric flow because of the different roughnesses of the river bed and vegetation cover. Moreover, its typical profile of streamwise velocity can be used for a rough estimation of the fate of solute transportation. In this study, a two-power law expression was adopted to predict the vertical profile of streamwise velocity. The influence of roughness of the floating vegetation patches and channel bed was also analyzed. To verify the model, the vertical distribution of longitudinal velocity and shear stress of a vegetation covered flow was investigated by laboratory measurements. Results showed that the location of the maximum streamwise velocity was close to the smooth boundary (i.e., the vegetation cover). The vertical profile of shear stress indicated that the turbulent structure was intensively influenced by the presence of vegetation cover and its roughness characteristics. In addition, the turbulence intensity values were amplified in the vicinity of simulated vegetation cover but reduced near the channel bed. The location of the maximum values of shear stress was close to the vegetation cover. The large values of shear stress near the vegetation canopy indicate the high turbulent levels because of the perturbation resulting from vegetation drag and the canopy gap.

1. Introduction

Floating vegetation is commonly seen in rivers, lakes, wetland marshes, and offshore environments (Bocchiola et al., 2002). Floating vegetation also is customarily planted in constructed floating wetlands (Rao et al., 2014). It can transfer biomass, nutrients, and energy across water (Dierssen et al., 2015), absorb nutrients and heavy metals to purify waste water (Hubbard et al., 2004), and finally achieve the goal of restoration of the river and lake ecosystems (Downing-Kunz and Stacey, 2012; C. Wang et al., 2015; C.Y. Wang et al., 2015). The existence of such rough covers (e.g., ice jam, floating vegetation, floating debris, and kelp beds) alters the flow structure and velocity distribution (Teal et al., 1994; Smith and Ettema, 1997). These changes derived from the vegetation cover not only influences sediment and contaminant transportation (Walker and Wang, 1997) but also affects phytoplankton and zooplankton biomass as well as the predation and habitat of fish communities (Adams et al., 2002; Padial et al., 2009). Therefore, investigating the flow structure of open channel covered with suspended vegetation is essential.

Compared with submerged or emergent vegetation, suspended vegetation can be categorized into two groups (Folkard, 2011), namely, rooted plants with floating leaves (e.g., water lilies, some pondweeds, and American lotus) and free-floating leaves with developed or under-developed roots (e.g., *Eichhornia crassipes*, duckweeds, and common bladderworts). Numerous studies regarding the open-channel flow with aquatic vegetation (submerged or emergent) have been carried out (Nepf, 1999; Stephan and Gutknecht, 2002; Maltese et al., 2007). However, the investigations on suspended vegetation flow were limited. Prior studies on floating vegetation have focused on vegetation that protrudes some distance into the flow (Plew et al., 2006; Huai et al., 2012; Plew et al., 2006, 2011; O'Donncha et al., 2015) rather than forming a thin layer on the surface (Downing-Kunz and Stacey, 2011, 2012). For example, Plew et al. (2006) found that the strong turbulence might enhance vertical exchange and turbulence dissipation within the suspended rigid cylinder array, and they further presented an analytical model with respect to the depth-averaged drag coefficient for open channel with rigid suspended canopy (Plew, 2011). O & Donncha et al. (2015) presented a three-dimensional hydrodynamic model by incorporating the influence of suspended canopy. Huai et al. (2012) adopted a three-layer model based on mixing length theory to simulate the flow structure of open channel flow covered by suspended rigid vegetation.

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http://dx.doi.org/10.1016/j.ecolind.2017.04.012
Received 31 December 2016; Received in revised form 14 March 2017; Accepted 6 April 2017
1470-160X/

For suspended vegetation floating on the water surface with undeveloped roots (Downing-Kunz and Stacey, 2012; Rao et al., 2014), the vegetation roughness and the channel bed roughness work together to the flow. The characteristics of flow with floating vegetation is akin to the ice-covered flow or duct flow, i.e., with a top rough cover, due to the additional drag force exerted by vegetation on the water surface and the bed friction on the bottom. The maximum velocity is located near the mid depth close to the smooth boundary rather than near the water surface for open water flow. For this reason, this covered flow has always been taken as the asymmetric flow (Hanjalic and Launder, 1972; Parthasarathy and Muste, 1994; Robert and Tran, 2012). To model the asymmetric ice-covered flow, Tsai and Ettema (1994) established a modified eddy viscosity model to predict the vertical profile of streamwise velocity to avoid the discontinuity of eddy viscosity. Robert and Tran (2012) found that the presence of floating cover can increase turbulent kinetic energy and Reynolds stress.

In this study, to investigate the vertical profile of streamwise velocity and turbulent characteristics under the combined action of the channel bed and vegetation cover, laboratory experiments were conducted in a flume covered with artificial lotus leaf. The velocity was measured by acoustic Doppler velocimeter (ADV). The two-power law expression was adopted to characterize the vertical profile of streamwise velocity and the boundary shear stresses that were related to the roughness feature of bed and vegetation cover. The position of zero shear stress and the influence of gaps among lotus leaves have been discussed.

2. Theoretical analysis

2.1. Two-power law expression for velocity profile

The maximum velocity is located near the mid depth and deflects to the smooth boundary due to the presence of floating canopy (Fig. 1). Therefore, this covered flow has always been taken as an asymmetric flow with two different roughness boundaries. One is associated with the bed and the other with the floating vegetation. Under the combined action of the upper and lower boundaries, the velocity profiles of vegetation covered flow are analogous to that of ice-covered flow. Moreover, the velocity profile was affected by the combined action of surface and bottom boundary roughness. However, the distinction between each other exists in some ways as follows: (i) the ice cover is commonly seen as a consecutive slab in open channel, which cannot move with flow except broken up but the vegetation cover in channels may exhibit different distribution patterns related to the vegetation type and population density and may drift with flow. (ii) Ice-covered flow is commonly taken as a pressure flow or strong analogy to the pressure pipe flow and the drag force acts on the river bank. However, the vegetation cover flow is a free flow with a variable population density. The drag force also acts on water surface.

As illustrated in Fig. 1, the vegetation covered flow can be divided into a bed zone and a vegetation zone by the horizontal plane of the maximum velocity u_{max}; h_b and h_v are the distances from u_{max} to the bed and vegetation cover, respectively; H is the flow depth; h_τ is the distance between the bed and the plane of zero shear stress; τ_b and τ_v are shear stress associated with bed and vegetation boundaries, respectively. Previously, the logarithmic velocity expressions and the two-layer hypothesis that considered the plane of maximum velocity as a free surface were employed to establish the vertical profile of averaged streamwise velocity. However, this method showed some drawbacks as follows: the gradient of velocity at the location of u_{max} is discontinuous, and the two-layer hypothesis was not suitable for ice-covered bend flows (Urroz and Ettema, 1994), and it overestimated the streamwise velocity near the location of velocity maximum (Lau, 1982).

Therefore, the vertical distribution of averaged streamwise velocity u is predicted by the two-power law expression (Tsai and Ettema, 1994; Uzuner, 1975), which is a continuous-gradient function and can avoid the drawbacks of discontinuous gradient caused by logarithmic velocity expressions and the two-layer hypothesis as follows:

$$u = K_0\left(\frac{z}{H}\right)^{1/m_b}\left(1-\frac{z}{H}\right)^{1/m_v} \tag{1}$$

where z is the distance from the boundary at which the streamwise velocity is u; K_0 is a parameter related to the per-unit-width discharge; m_b and m_v are the parameters relevant to the frictional effects of vegetation and riverbed, respectively. When m_v approaches infinity, Eq. (1) can be simplified to a single-power law expression for open channel flow $u = K_0(\frac{z}{H})^{1/m_b}$, and where K_0 becomes the u_{max}.

The theoretical position of the maximum velocity can be deduced by $\partial u/\partial z = 0$, and the maximum velocity is founded to be

$$u_{max} = K_0(h_b/H)^{1/m_b}(1-h_b/H)^{1/m_v} \tag{2}$$

and occurs at the position of h_b, where

$$\left(\frac{z}{H}\right)_{u_{max}} = \frac{h_b}{H} = \frac{m_v}{m_v+m_b} \tag{3}$$

A large boundary roughness exponent m indicates a smooth boundary and to which the maximum velocity u_{max} appears close (Hanjalic and Launder, 1972).

By integrating u by z, the depth-averaged velocity U can be obtained

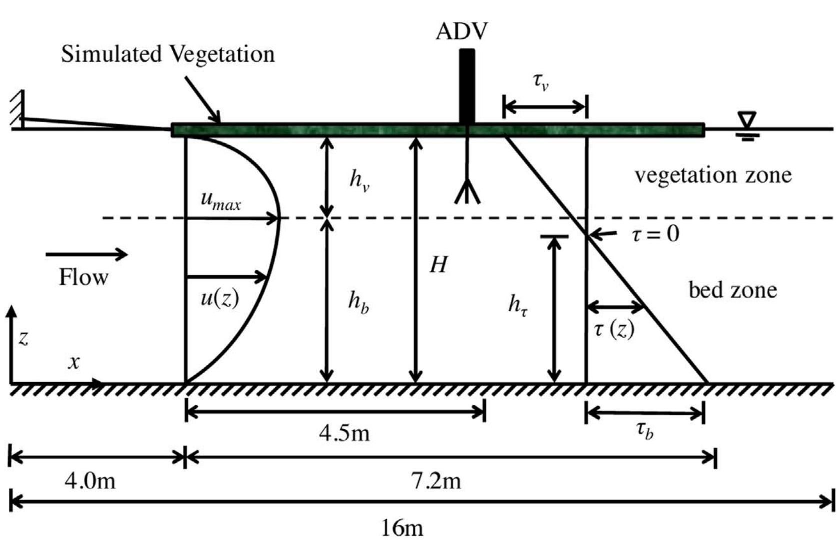

Fig. 1. Sketch of vegetation-covered flow in laboratory flume.