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Analytical model of the mean velocity distribution in an open channel with double-layered rigid vegetation

Wenxin Huai, Weijie Wang, Yang Hu, Yuhong Zeng *, Zhonghua Yang

State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, People's Republic of China

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ABSTRACT

An analytical model for predicting the vertical distribution of mean streamwise velocity in an open channel with double-layered rigid vegetation is proposed. The double-layered model was constructed in a laboratory flume with an array of steel cylinders of two heights. For each vegetation layer (i.e., the short- or tall-vegetation layer), the flow is vertically separated into a lower vegetation zone and an upper vegetation zone, and corresponding momentum equations for each zone are formulated. For the lower vegetation zone, a uniform velocity was adopted since turbulent shear is relatively small and the Reynolds stress is ignored. For the upper vegetation zone, a power series was used to solve the momentum equations. For the free-water zone, a new expression was suggested to obtain a zero velocity gradient at the water surface instead of the traditional logarithmic velocity distribution. Good agreement between the analytical predictions and experimental data demonstrated the validity of the model.

1. Introduction

Aquatic vegetation in open channels results in higher bed roughness, lower flow velocity and flood capacity. Thus, a better understanding of hydraulic characteristics in vegetated flow is important in the management of rivers and corresponding ecosystems. Interaction between flow and vegetation have been studied by different researchers, some of which attempted to develop resistance laws for vegetated flow [1–3], for example, Poggi et al. [4] investigated the hydraulic resistance of submerged rigid vegetation by first-order closure models, in which eddy viscosity was adopted to describe the turbulent stress. The Darcy-Weisbach friction factor (f) was shown to vary with three canonical length scales (i.e., water depth, vegetation height and the adjustment length scale) by conducting a simplified scaling analysis. Besides, a new analytical resistance model was proposed by Katul et al. [5] to assess the impact of vegetation on flood routing mechanics, and their analytical treatments reveals the resistance characteristics in flow through vegetation with different submergences. Konings et al. [6] proposed a new phenomenological model to deal with the vegetation resistance in flow by creatively linking the ejective and sweeping motions with their model. Some researchers focused on physical processes such as the bending of flexible vegetation in flowing water [7,8] and the energy exchange between vegetation and flow due to vortices [9,10]. Typically Nepf [11] investigated flow characteristics and mass transport in flow through submerged aquatic vegetation, indicating that the canopy can be divided into two regions: the upper canopy region which is controlled by canopy-scale vortices, and the lower canopy region where the turbulence is limited to smaller stem-scale.

Among hydraulic characteristics of vegetated flow in channels, the velocity distribution has been extensively studied since it is relevant to predicting discharge and flow patterns. Different models including the eddy viscosity model and the mixing length model have been adopted to predict velocity profiles, from which the roughness coefficient of vegetation and water conveyance and mass transport can be analyzed subsequently. The flow region has been vertically divided into two, three, or even four layers according to different closure models for the momentum balance equations. For example, Klopstra et al. [12] proposed an analytical model for submerged vegetated flow, in which turbulent shear stress was described by the eddy viscosity model of Boussinesq in the vegetation layer, and a logarithmic velocity profile was presented according to Prandtl's concept of the mixing length in the non-vegetation region. Baptist et al. [13] derived equations for the description of vegetation-induced roughness in several ways; the equations included analytical expressions and a numerical one-dimension vertical (1-DV) k–ε turbulence model [14], which is a simplification of the full 3-D Navier–Stokes equations to account for the horizontal component (1D) along the water depth

* Corresponding author. Tel.: +86 27 68772211.
E-mail addresses: wxhuai@whu.edu.cn (W. Huai), wjwang@whu.edu.cn (W. Wang), yhzeng@whu.edu.cn (Y. Zeng), yzh@whu.edu.cn (Z. Yang).

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(vertical direction). Huthoff et al. [15] presented an analytical solution of the depth-averaged flow velocity for submerged rigid cylindrical vegetation, which included a newly proposed brief scaling expression of the average flow field following fundamental laws of fluid flow. Huai et al. [16] proposed a three-layer model for open channels with rigid vegetation, in which the flow regime was divided into an upper non-vegetated layer, an outer layer and a bottom layer within vegetation, and both analytical and numerical models were adopted. Yang and Choi [17] proposed a two-layer approach for open-channel flow with submerged vegetation, and the velocity was assumed to be uniform in the vegetation layer and a logarithmic velocity profile was adopted in the non-vegetation layer. Furthermore, averaged velocities in the upper layer and entire layer, and the roughness coefficient of vegetation could be obtained from their velocity formula. Liu et al. [18] proposed an analytical solution for the vertical profile of horizontal velocity within submerged shrub-like vegetation based on the momentum theorem and mixing-length turbulence model. For the flexible vegetation in open channel flow, Huai et al. [19] proposed a two-layer velocity model, which took the bending of vegetation into consideration.

The models proposed above are for vegetated flows with uniform vegetation height and shape. However, in the natural riparian environment, vegetation has different heights and shapes. When the flood rate is large enough, both short and tall vegetation will be submerged; while, when the flood is not so large, the short vegetation is submerged and the tall is emergent. During this situation, the interaction between the tall layer and the short layer will lead to a quite different velocity distribution from the single-layered emergent or submerged cases. Liu et al. [20] investigated the response of turbulent flow through a double-layered rigid vegetation, and the vegetation density was denser in the short vegetation layer and sparser above it to simulate a combination of short and tall vegetation in natural environment. In their experiments, both linear and staggered arrangements were adopted, and the flow velocity and turbulence intensity profiles were collected by a one-dimensional laser Doppler velocimeter at multiple locations. Their results illustrated the hydraulic characteristics from many aspects. For the streamwise velocity, it is nearly constant in the lower part and begins to increase in the upper part within each vegetation layer when submerged. Due to the denser arrangement of the short vegetation layer, the flow in it is slower than that above it. They also explored the influence of vegetation density and heights on flow: the vegetation density is a factor that determines the scope of the constant velocity zone, and this zone will vanish under the influence of coherent structures if the height difference between the tall and short stems is small enough.

Although many studies were conducted on the velocity profile in vegetated flow, only a few focused on the case with double-layered vegetation. For some of the situations, the double-layered vegetation in open channel can be regarded as rigid when the flexural rigidity is high enough. The goal of this paper is to establish a simplified analytical model for predicting the vertical distribution of mean streamwise velocity in open channel with double-layered rigid vegetation. The flow can be divided into different zones according to different submergence conditions, and corresponding momentum equations for each zone are formulated to obtain the analytical solution. This work is an extension of our previous work about the single-layered vegetation, and a power series method [21] was adopted in this paper.

2. Theoretical analysis

For a uniform, steady and fully developed turbulent open-channel flow with the double layers consisting of rigid cylindrical stems with two heights h_1 and h_2 ($h_2 > h_1$), as illustrated in Fig. 1, the flow can be separated into three cases according to the water depth H; i.e., $H < h_1$, $h_1 < H < h_2$, and $H > h_2$. Note that when the water surface is lower than the short stems (i.e., $H < h_1$), the situation is the same as traditional non-submerged single-layer vegetated flow [22,23], and this case will not be discussed here. In this paper, we discuss the two remaining cases; i.e., $h_1 < H < h_2$ (Fig. 1(a)) and $H > h_2$ (Fig. 1(b)).

From Fig. 1, each vegetation layer is represented by Arabic number, i.e., layer 1 denotes the short-vegetation layer and layer 2 denotes the tall-vegetation layer, indicating the part where the vegetation stems taller than the short ones with a thickness of (h_2–h_1). Close to the channel bed, there is a thin shear layer, which can be ignored in the analytical models [12,13,17,18]. According to the investigation conducted by Liu et al. [20], each vegetation layer is divided into two zones (Fig. 1): the lower vegetation zone (represented by the letter A) where the mean velocity is nearly constant, and the upper vegetation zone (represented by the letter B) where the mean velocity increases significantly. Each zone in different layers was represented by "layer number" plus "A" or "B". For example, the lower vegetation zone in short-vegetation layer is represented by zone 1A. When $h_1 < H < h_2$, the short-vegetation layer is submerged and the tall-vegetation layer is emergent (Fig. 1(a)), there is a lower vegetation zone 1A and an upper vegetation zone 1B in layer 1; and a lower vegetation zone 2A in layer 2. When $H > h_2$, both the short and tall vegetation are submerged (Fig. 1(b)), each vegetation layer can be divided into a lower vegetation zone A and an upper vegetation zone B. Above the tall-vegetation layer, there is a free-water zone (Fig. 1(b)).

In regions where vegetation exist, the momentum equation can be expressed as

$$\frac{\partial \tau}{\partial z} + \rho g i - F_d = 0 \tag{1}$$

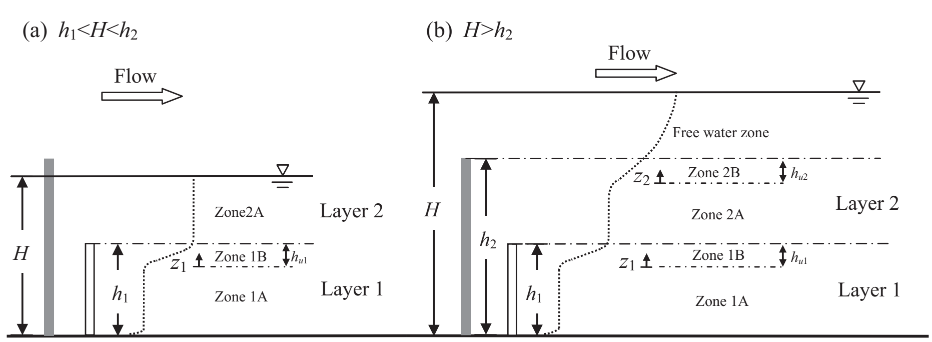

Fig. 1. Sketch of open-channel flows with double-layered vegetation; (a) and (b) show the scenarios of different degrees of submergence.