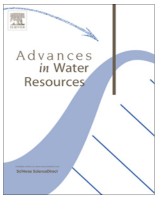
Advances in Water Resources 60 (2013) 148–159

Contents lists available at ScienceDirect

Advances in Water Resources

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



Modeling depth-averaged velocity and bed shear stress in compound channels with emergent and submerged vegetation

Chao Liu [a], Xian Luo [b], Xingnian Liu [a], Kejun Yang [a,*]

[a] State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu, Sichuan 610065, China
[b] School of Information Sciences and Engineering, Chongqing Jiaotong University, Chongqing 400074, China

ARTICLE INFO

Article history:
Received 19 August 2012
Received in revised form 23 July 2013
Accepted 1 August 2013
Available online 14 August 2013

Keywords:
Vegetation
Compound channels
Depth-averaged velocity
Bed shear stress
Secondary flows

ABSTRACT

This paper presents an approach to modeling the depth-averaged velocity and bed shear stress in compound channels with emergent and submerged vegetation. The depth-averaged equation of vegetated compound channel flow is given by considering the drag force and the blockage effect of vegetation, based on the Shiono and Knight method (1991) [40]. The analytical solution to the transverse variation of depth-averaged velocity is presented, including the effects of bed friction, lateral momentum transfer, secondary flows and drag force due to vegetation. The model is then applied to compound channels with completely vegetated floodplains and with one-line vegetation along the floodplain edge. The modeled results agree well with the available experimental data, indicating that the proposed model is capable of accurately predicting the lateral distributions of depth-averaged velocity and bed shear stress in vegetated compound channels with secondary flows. The secondary flow parameter and dimensionless eddy viscosity are also discussed and analyzed. The study shows that the sign of the secondary flow parameter is determined by the rotational direction of secondary current cells and its value is dependent on the flow depth. In the application of the model, ignoring the secondary flow leads to a large computational error, especially in the non-vegetated main channel.

1. Introduction

In natural rivers, vegetation often grows along both banks and on floodplains, thus generating complex velocity fields, which in turn influence flow resistance and hence the discharge capacity of the channel [63]. Due to the velocity difference between vegetated and non-vegetated domains, strong shear layers and large planform vortices occur. In these circumstances, the strong mass and momentum exchanges affect both the velocity field and bed shear stresses that, in turn, may influence sediment transport and bank stability [5,23,24,30]. Accordingly, there is a need to assess the effects of vegetation on flow parameters, such as secondary flows, velocity, bed shear stress and discharge.

In modeling open channel flows, secondary currents play an important role [22,40] since they affect the primary mean flow and boundary shear stresses [59]. Due to their theoretical importance and practical impact, many investigations have been conducted to investigate secondary flows in simple and compound channels in recent decades. Odgaard [33] proposed a simple analytical relationship between the strength of secondary currents and the transverse variation of bed shear stress and evaluated the effect of secondary currents on the streamwise velocity profile. Ikeda [16] discussed the structure of secondary current cells and proposed an analytical expression for describing them. Tominaga and Nezu [58], and Tominaga et al. [59] investigated the secondary flows in single and compound channels and discussed their effects on momentum transfer, velocity and boundary shear stress. Shiono and Knight [40] found that there are generally two major secondary current cells in the vicinity of the main channel side slope region. Shiono and Feng [39] conducted experiments in both rectangular and compound channels to investigate the effects of secondary currents on passive contaminant diffusion processes. Wang and Cheng [60,61] experimentally investigated the characteristics of secondary flows generated by longitudinal bedforms and artificial bed strips. Blanckaert et al. [4] studied the influence of shallowness, bank inclination and bank roughness on the variability of flow patterns and boundary shear stress due to secondary currents in straight open channels. Jing et al. [19,20] applied a numerical model to simulate the effect of secondary currents in meandering compound trapezoidal open channels. However, due to the influence of vegetation, the secondary flow structure is altered dramatically [37,63]. Yang et al. [63] observed the extremely complex distribution of secondary flows in the main channel side slope domain, with some minor but strong secondary current cells on the vegetated floodplain. Sanjou et al. [37] have measured the secondary flow distributions in rectangular compound channel

---

* Corresponding author. Tel.: +86 28 85401937.
E-mail address: yangkejun@scu.edu.cn (K. Yang).

0309-1708/$ - see front matter Crown Copyright © 2013 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.advwatres.2013.08.002

Notation

The following symbols are used in this paper:

A_1, A_2, C_1, C_2	integration constants in Eqs. (14) and (16)
B	distance from centerline to floodplain edge
b	semi-width of main channel
C_d	drag force coefficient
D	vegetation diameter
D_r	relative depth ratio, $(H-h)/H$
f	Darcy–Weisbach friction factor
F_v	drag force, defined by Eq. (3)
g	local gravitational acceleration
H	total flow depth
H_v	vegetation height
h	bankfull height
h^*	relative height coefficient, defined by min $[H_v, H]/H$
$\bar{K}$	modified secondary current coefficient
k_s	equivalent sand roughness height
k_v	coefficient, define by Eq. (7)
m	vegetation number per unit bottom area
n	Manning's coefficient
N	number of measured depth-averaged velocity
S_0	channel bed slope
s	channel bed side slope
U, V, W	velocity components in the x, y, z directions
U_d	depth-averaged streamwise velocity, defined by Eq. (2)
U_v	depth-averaged streamwise velocity around vegetation, defined by Eq. (5)
U_*	shear velocity
V_{column}	volume of a water depth column per unit vegetated-bottom area
$V_{vegetation}$	volume occupied by vegetation per unit vegetated-bottom area
x, y, z	streamwise, lateral and vertical coordinates, respectively
α	porosity
β	shape factor
λ	lateral dimensionless eddy viscosity
ε_a	absolute error, defined in Eq. (19)
$\overline{\varepsilon_a}$	average absolute error, defined in Eq. (20)
$\overline{\varepsilon_r}$	average relative error, defined in Eq. (21)
ξ	flow depth function in side slope domain
ν	kinematic viscosity
κ	Karman constant
Φ	calculation coefficient, defined by Eq. (17)
ω	coefficients in Eqs. (14) and (16)
$\bar{\varepsilon}_{yx}$	depth-averaged eddy viscosity, defined by Eq. (2)
τ_b	boundary shear stress
$\overline{\tau_{yx}}$	depth-averaged Reynolds stress on the plane perpendicular to the y direction; and
ρ	flow density

Subscripts

1–4	panel number
mc	main channel and
fp	floodplain

with one-line trees along the floodplain edge, showing that a counterclockwise secondary current cell takes place in a non-vegetated main channel while a clockwise one rotates on the vegetated floodplain. Rameshwaran and Shiono [36] showed that the secondary flow parameter, defined in terms of the lateral gradient of the secondary flow force per unit length of the channel, varied linearly with the flow depth in vegetated compound channels while the non-vegetated cases were different [40]. The results of Stone and Shen [46] and Poggi et al. [35] showed that the flow resistance varied with the flow depth, the density, height and diameter of aquatic vegetations. Thornton et al. [57], Nezu and Onitsuka [32], Yang et al. [63], Hopkinson and Wynn [12] and Sukhodolov and Sukhodolova [48] investigated the effect of vegetation on the three-dimensional (3D) structure and turbulence characteristics of the flow. In addition to the velocity distribution for open channel flows with suspended vegetation, Huai et al. [14] investigated the mechanism of energy loss and transition in a flow with submerged vegetation. Chen et al. [6] experimentally investigated the effects of submerged vegetation on the characteristics of the flow and on bed erosion. Perucca et al. [34] analyzed the dispersion coefficient in rivers with riparian vegetation. In addition, flow characteristics of one-line emergent vegetation along the floodplain edge of a compound channel have also been studied by Sun and Shiono [49], Shiono et al. [42], Terrier [56] and Keshavarzi and Esfahani [21]. Their studies showed that the flow structure, velocity, discharge and boundary shear stress were significantly influenced by the presence of vegetation. On the other hand, the drag force, which was closely related to the vegetation density, significantly contributed to the total flow resistance.

The problem of vegetated compound channels has also been addressed extensively by means of numerical modeling methods, including large eddy simulations [8,28,44,45,47], two-dimensional lattice models [18], Reynolds Stress Models [7,11,19,20,29] and other models [9,17,26,31,51]. In addition to numerical methods, analytical methods for the distributions of velocity and boundary shear stress in vegetated channels have also been proposed. Huai et al. [13] developed a three-layer model to determine the vertical velocity distribution in open channel flows with submerged rigid vegetation. Based on the Shiono and Knight method (here after referred to as the SKM) [40], Tang and Knight [54] and Tang et al. [52] proposed modified models to predict lateral distributions of depth-averaged velocity and bed shear stress in vegetated compound channels. In order to evaluate the effect of one-line vegetation along the edge of floodplain on the flow field, Sun and Shiono [50], Shiono et al. [42,43] and Terrier [56] modified the SKM by incorporating drag forces induced by the one-line vegetation, which led to new analytical solutions for depth-averaged velocity and bed shear stress. Other analytical method of depth-averaged velocity was given by Huthoff et al. [15], based on the two-layer approach, which has recently been developed further by Konings et al. [25] to account for the momentum contributions generated by ejections and to include constraints imposed on the eddy sizes on the basis of their abilities to penetrate the canopy. Furthermore, White and Nepf [62] proposed a model for the vortex-induced exchange to predict the depth-averaged velocity and shear stress.

Although many predictive models have been proposed for the lateral distributions of depth-averaged velocity and bed shear stress in vegetated compound channels, they mainly focus on the emergent vegetation. However, the compound channel with submerged vegetation is a common feature in natural rivers and predictive models are rarely found. Furthermore, how to reasonably describe the effects of secondary flows in a compound channel with vegetation is also a challenge. Therefore, a model which