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Research Paper

Transverse distribution of streamwise velocity in open-channel flow with artificial emergent vegetation

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ABSTRACT

Artificial emergent vegetation can increase flow resistance and water depth to improve navigation in an open channel. An innovative and eco-friendly artificial vegetation system is analyzed in this study. First, a new method is presented to modify the depth-averaged Navier–Stokes equation by incorporating the vegetation drag force term. Two analytical formulas based on theoretical analysis are proposed to predict the lateral distribution of depth-averaged velocity in an open channel with fully and partially artificial vegetation. Then, the analytical formulas are verified by laboratory experiments. The results of the analytical model are consistent with experimental data, thereby proving that the analytical formulas can be used to predict the lateral distribution of streamwise velocity in open-channel flow with artificial emergent vegetation. The presented model can provide a significant theoretical reference for research on open channels with artificial emergent vegetation.

1. Introduction

Artificial vegetation is rarely studied despite being an important and controllable vegetation form in open channels. An innovative soft method was proposed by placing artificial vegetation in an open channel to improve navigation by increasing water depth (Zdankus et al., 2016). Many studies on open-channel flow with vegetation indicate that vegetation can inevitably change flow structure and mass transport (Fonseca and Fisher, 1986; Huang et al., 2002; Lee et al., 2004; Cattrijsse and Hampel, 2006; Ghisalberti and Nepf, 2006; White and Nepf, 2007; Cheng, 2011; Pang et al., 2014; Devi and Kumar, 2016a; Devi and Kumar, 2016b). For example, vegetation can decrease vortex size, thereby impeding mass transport in the vertical direction and reducing the mixing and degradation rates of contaminants or nutrients in rivers (Zhang et al., 2009; Nepf, 2012). In addition, the distribution of streamwise velocity plays a significant role in the research on longitudinal dispersion because the longitudinal transport of solutes depends on the longitudinal advection in rivers (Wang and Huai, 2016; Wang et al., 2017). Therefore, velocity distribution in open-channel flow with artificial emergent vegetation should be studied.

The lateral distribution of streamwise velocity in an artificially vegetated channel can be obtained on the basis of the depth-averaged Navier–Stokes (N–S) equation. The depth-averaged form of the N–S equation in the main flow direction was initially proposed for non-vegetated channels (Shiono and Knight, 1991). The problem of lateral distribution of velocity for flow through vegetation has been studied extensively, and the forms of vegetation are mostly cylindrical. The drag force term due to cylindrical vegetation is added into the depth-averaged N–S equation and then the N–S equation has been improved in some aspects. For example, according to mixing layer theory, a vegetated channel in cross section can be divided into several subareas, and the model parameters in the N–S equation are different among all the subareas (White and Nepf, 2008; Huai et al., 2013; Liu et al., 2013; Fernandes et al., 2014). A dimensionless form of the N–S equation, avoiding the disadvantages of the dimensional form and distinguishing the influence of friction and gravity, was proposed to obtain velocity distribution (Chen et al., 2010; Huai et al., 2011). The reliability of depth-averaged velocity and boundary shear stress may be enhanced by improving the algorithm of the friction coefficient *f*, eddy viscosity coefficient, secondary flow coefficient, and so on (Rameshwaran and Shiono, 2007; Huai et al., 2008; Huai et al., 2009; Devi and Khatua, 2016).

Cylindrical vegetation in vegetated channels have drawn considerable attention. The previous calculation methods for vegetation drag force can not be directly used in the present study as the artificial vegetation form is distinctive. The artificial vegetation, which we call a "damper," consists of a series of floats connected by a thin rope. The projection height of the artificial vegetation in the vertical direction is equal to and changes with water depth (Fig. 1). In the depth-averaged N–S equation, the drag force caused by vegetation is the sum of the resistances of the floats. The secondary flow coefficient is ignored by

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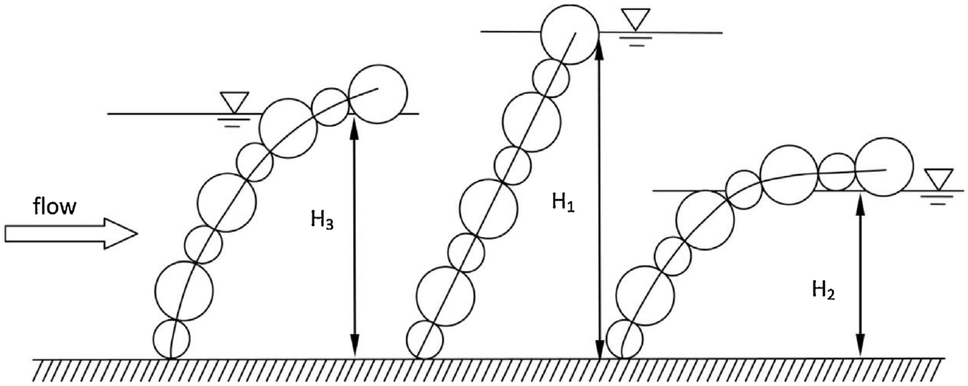

Fig. 1. Form and projection height of the artificial vegetation for different water depths. The small and large circles represent floats, which are connected by a thin rope.

defining it as zero for the fully vegetated channel. However, the secondary flow term is considered in the equation and the flow is divided into two subareas (i.e., non-vegetated and vegetated) along the transverse direction when the channel is partially covered by artificial plants. Taking all the above into consideration, an improved theoretical model of depth-averaged N–S equation is proposed in this article. Laboratory experiments are used to verify the accuracy of this model and provide a detailed turbulent flow structure with different artificial plant coverage levels in open channels. The results of the proposed model agree well with the available data from laboratory experiments, thereby proving that the analytical model is reasonable and that the analytical solutions to the proposed model can serve as references for problems of turbulent flow with artificial plants.

The main objective of this work aims to use the depth-averaged N–S equation and laboratory experiments to investigate velocity distribution in open channels with artificial emergent vegetation. The details of the laboratory experiments and the form of vegetation damper are described in Section 2. The two analytical solutions of velocity distributions in the open channel fully and partially covered by artificial vegetation are investigated in Section 3. The calculation methods for the parameters in the theoretical model are explained in Section 4. In Section 5, we compare the experimental data with theoretical analysis results using diagrams and the errors between the data from the experiments and from the theoretical analysis are analyzed. Conclusions are presented in Section 6.

2. Experimental study

The experiments were conducted in a rectangular flume, which was 20 m long, 1 m wide and 0.4 m deep with a bed slope S = 0.001 in the State Key Laboratory of Water Resources and Hydropower Engineering Science in Wuhan University. The water depth was kept constant by adjusting the tailgate at the end of the flume and the electromagnetic flowmeter. The experimental setup is shown in Fig. 2. The two conditions of the field experiment are shown in Fig. 3. The channel fully covered by dampers is shown in Fig. 3(a), and the partially covered channel is shown in Fig. 3(b).

All dampers should remain in a normal state with the forces of gravity and buoyancy. A damper that consists of only white hollow floats or only red solid floats will be in an abnormal state with the prevailing forces of buoyancy or gravity. Therefore, each damper is constructed by four white hollow floats and four red solid floats (Fig. 4). The eight floats are connected in certain patterns by a thin rope. When the floats are put randomly, two kinds of influence on the flow structure may appear. First, the arrangement of floats which are put randomly is shown in Fig. 5a. Comparing with morphology of vegetation (Fig. 4a), the morphology of the vegetation in the flow does not change significantly. Second, the arrangement of floats (Fig. 5b and c) would result the great changes of flow structure. When the water depth is small, such as H_1 = 12 cm, the four soild floats are completely submerged (Fig. 5b). The gravity dominates buoyancy in this situation, which leads that the floats may be sheltered a lot by other floats and eventually causes that the resistance of vegetation to water flow is reduced. When the water depth is large, such as H_2 = 20 cm, all the floats can be completely submerged (Fig. 5c). Owing to the diameters difference of soild and hollow floats, the resistance in the upper layer is larger than that in the lower layer. Hence, the two-layer flow structure can be formed because of the discontinuous resistance caused by floats. However, when the floats are put in a certain pattern, the flow structure is more uniform in the vertical direction.

The diameters of the white hollow floats and the red solid floats are 0.04 and 0.02 m, respectively. The projection height of the damper changes with water depth and the damper extends from the bottom of the bed to the water surface, therefore, the damper can be treated as emergent vegetation. *N1* and *N2* are the numbers of white hollow floats which are completely and incompletely submerged. *N3* and *N4* are the numbers of red solid floats completely submerged and incompletely submerged, respectively. For example, when the water depth is *H* = 20 cm, the number of white hollow floats which are completely submerged is *N1* = 3, and the number is *N2* = 0.5 for incompletely submerged hollow floats. For red solid floats which are completely submerged, the number is *N3* = 4, and the number of incompletely

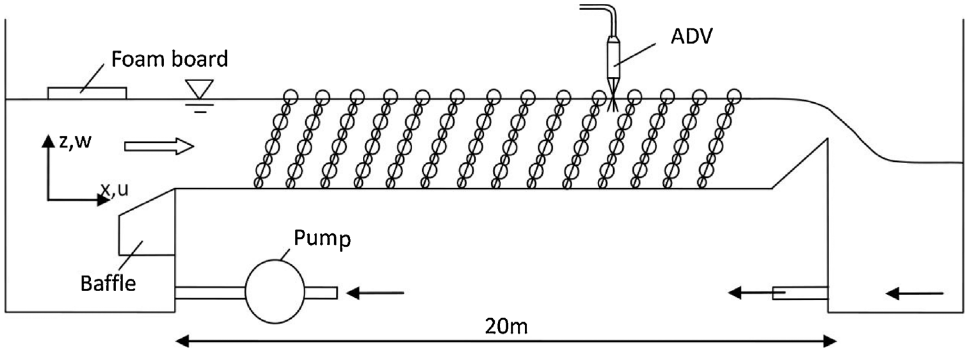

Fig. 2. Schematic diagram of the experimental device.