Study on velocity profile and drag coefficient of flow through double layer vegetation

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ABSTRACT

The present paper studies the characteristics of flow that passes through two-layer vegetation in open channels under emergent and submerged conditions for short and tall vegetation respectively. Various discharges and flow depths have been studied to provide a comprehensive sight of flow details through the vegetation layers, which are modelled by cylindrical dowels with 6.35 mm diameter and two heights of 10 mm and 20 mm installed in a 10 mm thickness. Flow velocity in different locations was measured by a Nortek ADV velocimetry.

The velocity profiles in single layer vegetation under emergent condition show a uniform constant velocity all over the flow depth. In our study, experimental data indicate that there is more complexity around the edge of short vegetation which could be due to vortex shedding existence. Drag coefficient as a resistance parameter, has a larger value compared with open channel without vegetation. More specifically, in vegetation layers the resistance parameters are found to be dependent of the flow depth and submergence condition, on the other hand channels without vegetation usually has a constant roughness coefficient. When the short vegetation was fully submerged, the drag coefficient reduced through the flow depth. Meanwhile, drag coefficient showed a reverse tendency in mixed layer condition.

Velocity profiles measured in different locations and depths indicate that location is an important factor to velocity profiles. The velocity profile above the short vegetation in two-layer vegetation conditions is much larger than that in single layer conditions. Generally, the flow velocity inside the vegetation layer is significantly smaller than that in the surface layer (i.e. non-vegetation layer). A near-constant velocity dominates inside the vegetation layer, and then starts to increase near the interface at the top of vegetation. There is a sudden change in the velocity profile near the top edge of short vegetation. The results also showed that in channels with double layer vegetation, the flow velocity is strongly dependent on locations.

KEY WORDS: Double layer vegetation, open channel flow, drag coefficient, velocity profile.

INTRODUCTION

The existence of vegetation in open channel flows such as rivers cause a loss of energy through turbulence and add additional resistance on the flow. On other words, vegetation increases the drag resistance and therefore play an important role in river and water environment engineering. The drag coefficient, one of the most important parameters of flow resistance, depends on many factors such as vegetation density and configuration. Vegetation could be bushes, trees, herbs or any other kinds of plant which of course has different stem heights. Previous experimental studies mostly simulate just one kind of vegetation with a specific height, which is far away from the reality of natural rivers or any other natural open channels. Resistance parameters such as drag coefficient are still under investigation due to lake of understanding of complex flow hydrodynamics phenomena (Yen, 2002; Zima and Ackermann, 2002). Although some researchers have studied the flow characteristics through emergent and submerged conditions (Wessels and Strelkoff, 1968; Li and Shen, 1973; Stone and Shen, 2002; Cheng and Nguyen, 2011), only few limited studies have been studied about double layer vegetation with emergent and submerged conditions at a same time. After the literature is reviewed, it is poor understanding on different hydraulic parameters of flow with double layer vegetation. The present paper is to study the drag coefficient (one of the most important resistance parameters) and velocity profiles for different flow depths.

LITRETURE REVIEW

Generally, the resistance of flow in open channel flow is a complicated topic and there is no accurate method to determine it (Jarvela, 1998). Based on Chow (1959)'s study there are some important parameters which influence the resistance of open channel flows such as size, shape and irregularity of the channel, and types and formation of vegetation.

In 1969 Kouwen et al. did a laboratory research by using plastic strips for vegetation simulation, and then they proposed formulae to compute the average velocity of the channel and used that for drag coefficient estimation. In the same year Petryk evaluated the drag force on each circular cylinder in different arrangements under different flow conditions. The study investigated the effect of other cylinder formation on the test cylinder and reported that the mean drag of the group of cylinders could be different from an isolated cylinder. Li and Shen (1973) studied the relations between vegetation arrangements and drag coefficient, and concluded that the vegetation formation and density have a remarkable effect on flow resistance. Blevins (2005) used aquatic plant stem for the vegetation simulation and found that the value of drag coefficient, CD, decreased with increasing value of Reynolds Number.

Wu et al. (1999) simulated bush type vegetation in open channel flow, and they reported that the value of drag coefficient has a linear relationship with the flow depth in a vegetated channel. Kothayri et al. (2009) used strain gauge to measure the drag force on a cylindrical dowel in the middle of vegetation zone. They observed that the drag coefficient increased slightly in higher Reynolds number, and that this coefficient also increased in higher vegetation density.

Li and Shen (1973) performed some comprehensive experimental work on a group of cylinders with different configurations in non-submerged flow conditions. Their experimental results indicated that flow depends strongly on by patterns or groupings. They found that the most effective factors on the drag coefficient are such as the flow turbulence, non-uniform velocity profile, free surface effects, and effect of blockage.

The hydraulic resistance using cylindrical roughness has been investigated by Stone and Shen (2002), who revealed that CD is not accurate enough to estimate the drag coefficient. Hence, they defined a revised drag coefficient, CDm, based on the constricted cross-sectional velocity Uc that it is much close to the drag coefficient of a single cylinder. The relationship between CD and CDm is:

$$C_D = C_{Dm}\frac{U_c^2}{U_l^2} \qquad (1)$$

where U_l and U_c are the apparent vegetation layer velocity and the surface layer velocity.

METHODOLOGY

Experimental Study

Experiments were conducted at Hydraulic laboratory of Nanjing Hydraulic Research Institute, China., in a 12 m long by 0.4 m wide straight flume at a constant slope of 0.004 (Fig 1).

The vegetation was modelled by circular dowel cylinders (Fig 2). The rigid cylinder array is ideal for modelling the flow-vegetation interaction, as it provides a reasonable morphological approximation of the stem region. 10 mm thickness plate with holes being installed the dowels was placed at the flume bottom to simulate the vegetation (Fig 3). The artificial vegetation covers a 7 m long portion of the flume and the tailgate at the end of the channel is used to adjust different flow depths (Fig 4). The used cylindrical dowels are 6.35 mm diameter at two heights of 100 mm and 200 mm.

Figure 1. Flume

Figure 2. Circular dowels

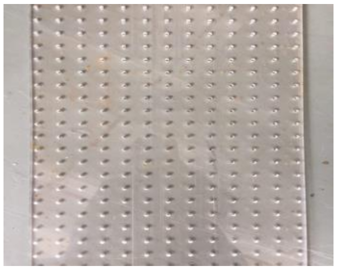

Figure 3. Plate

Figure 4. Tailgate

Experimental plan has been designed to study the drag coefficient and velocity profiles in (Fig 5). The spacing is a major factor for dowel configuration, which is defined by the non-dimensional parameter of s/d, in which s and d represent the spacing of dowel’s canters and its diameter, respectively. Three locations have been chosen to provide comprehensive details as water passes through vegetation. As it can be seen from Figure 5, location 1 represents the location behind the tall dowel and in front of short one, location 2 indicates the region behind the short dowel and in front of tall one, and location 3 is located in free region between dowel columns.

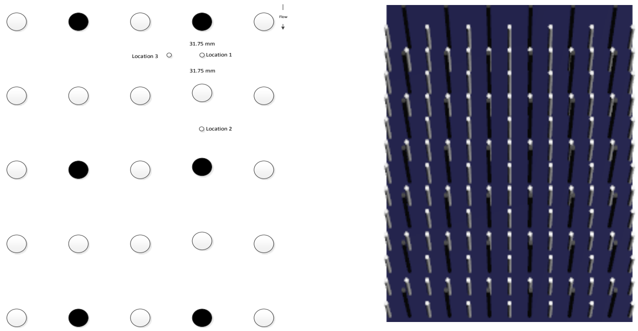

Figure 5. Dowel arrangement for experiment. The black and white circles represent tall and short dowels respectively. The arrow shows the flow direction. o also represent the measurement points by

Details of experiments have been shown in table 1.

Table 1. Details of arrangement.

Experiment	Dowel Height (mm)		Dowel Spacing (mm)		Dowel Arrangement	
	Short	Tall	Short	Tall	Short	Tall
1	10	20	63.5	127	Linear	Linear

The main measuring parameters are depth of flow, discharge, bed slope, and velocity of the water. The depth of flow was measured by point gauge which was installed to the travelling holder. An Acoustic Doppler Velocimeter (ADV) was used to measure the velocity of different depths at various locations in the vegetation section (Fig. 6). The ADV was mounted vertically on a guide rail and can be adjusted to move either in the vertical or in the lateral direction across flume width. The point gauge was also attached to the carriage and can be moved in both longitudinal and transverse directions.

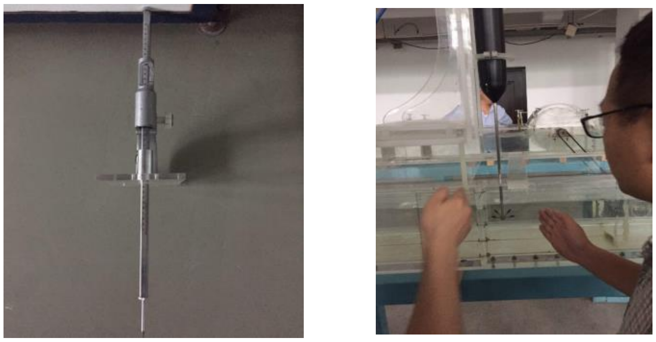

Figure 6. Point gauge and Nortek ADV

Table 2 indicates the details of experiments in different flow depths, which has been chosen in order to make short vegetation fully submerged and tall ones emergent.

Table 2. Details of experiments.

Discharge Q (m3/s)	Dowel Spacing (mm)		Dowel Arrangement		Depth of flow (cm)	Average Velocity (m/s)
	Short	Tall	Short	Tall		
0.014	63.5	127	Linear	Linear	12.6	0.205
0.018					14.9	0.235
0.023					17.3	0.268
0.025					19.4	0.291

Numerical Study

The flow of double layer vegetation was modelled by the numerical method via CFD.

Computation domain

In this study a 3D model was constructed with four boundary types: velocity inlet, pressure outlet (outlet and upper section of the model), symmetry and wall. Inlet velocity is the first case set to 0.2 m/s and outlet gauge pressure is set to 0 which represents the atmospheric pressure (operating pressure) of zero.

Given the inlet velocity of 0.2 m/s, the flow Reynolds number is calculated to be 16600 and is considered to be fully turbulent; thus, flow turbulence is modeled using k-ε model and von-Karman standard wall functions is used to capture gradients of velocity in the vicinity of viscous sub layer.

In order to obtain the independent results free from the effect of cell sizes, three meshes with different sizes were generated in ANSYS-ICEM CFD. In this section, the mesh sensitivity results from cell sizes have been proven as it was shown that changing the sizes of the network does not noticeably change the results. Thus, generated mesh with 1,785,047 cells was used to calculate the flow characteristics throughout the numerical analysis (Figure 7). The finer dimension of the grid has no effect on the velocity distribution and turbulent intensity of the flow. So, the results are independent of the grid sizes. Since the velocity gradient is very large in a direction perpendicular to the wall around the cylinder, boundary layer mesh was used close to the wall and the size of the first cell at the boundary of the cylinder wall was assigned to be 0.0014 m.

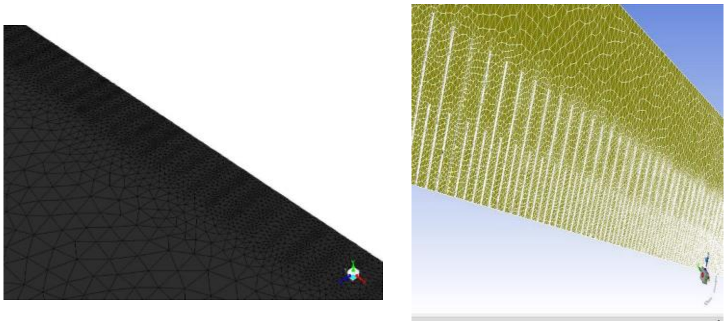

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Figure 7. Schematic of validation meshing and modeling with more than 1 million cells.

Definition of boundary conditions

There are several conditions at the inlet or outlet boundaries where the fluid enters or leaves the computational domain. These boundaries are usually categorized as the condition at a specified velocity or with a specific pressure. Due to the pairing of the pressure and velocity in the momentum equations, only one of the two conditions of pressure or speed is defined. For the inlet boundary condition, the velocity value is determined along x coordinate with the different values of velocity such as U = 0.2 m/s, and for the outlet boundary condition, the static pressure is determined through the outlet, which is the same atmospheric pressure as the relative pressure is zero.

For the parameters of turbulence in the inlet and outlet, the following correlations are used:

$$I=0.16^{(Re)^{1/8}} \qquad (2)$$

$$l=0.07D \qquad (3)$$

In the above correlations, I represents the turbulent intensity defined as follows:

$$I= u'_i / u_i \qquad (4)$$

The length of the turbulence scale indicates the size of the large vortices in the turbulent flow, and D is the diameter of the dowels. The values of I are 5%, respectively.

Boundary conditions of the wall

For dowels arrangement, a wall boundary condition is used. Since the fluid does not cross the wall, the vertical component of the velocity is zero relative to the wall. In addition, due to the no-slip wall condition, the tangential component of the velocity is also zero. In the upper side boundaries, the pressure is considered atmospheric and relatively zero. Also, in order to simplify the current modeling, the Symmetry boundary condition is used (no-shear wall) at the right side of the model.

Model analysis in the ANSYS-Fluent Solver

In the present analysis, an incompressible water fluid with a density $p = 1000\ (kg/m^3)$ and dynamic viscosity of 0.00104 has been used. The k-ε model was used to model turbulence. SIMPLE algorithm was used to solve the governing equations and all equations were performed with second order upwind discretization. For convergence of solutions, the model was first solved in the steady state, then solved in the unsteady state and time-variant with time step size of 0.05s and number of time steps of 700 to 1000.

Analytical Study

As flow passes through vegetation, drag force is produced which follows with velocity gradients and eddies, and causes momentum loss. Channels with high density vegetation experienced higher momentum losses in comparison of lower denser channels or open channel flows without vegetation. Stone and Shen (2002) did some valuable experiments specifically on drag coefficient of single layer vegetation in different flow and formation conditions. They proposed Equation 3 to estimate the value of drag coefficient in different locations.

$$C_d = \frac{g(1-\lambda l^*)\pi ds}{2\lambda l^* v_c^2} \qquad (3)$$

where g is the acceleration due to gravity, λ is the vegetation density, l* is the submergence ratio which is the ratio of wetted stem length to the depth of water flow, d is the diameter of vegetation which is simulated by dowels, S is bed slope of the channel, and V_c is the velocity of flow in the vegetation layer.

In this study, the drag coefficient CD for double layer vegetation is defined based on Equation 3, which shows that the drag coefficient is related to l*. For the emergent condition, l* = 1, and the velocity of vegetation layer is independence of flow depth. But when the short vegetation is under submerged condition, l* < 1, which depends on a flow depth.

As seen in Equation 4, we propose a new parameter l^*_{new} which is defined as an average of submergence ratios in both emergent and submerged conditions. The new parameter is directly related to the flow depth because each depth has its specific value of l*.

$$l^*_{new} = \frac{l_s^* + l_e^*}{2} \qquad (4)$$

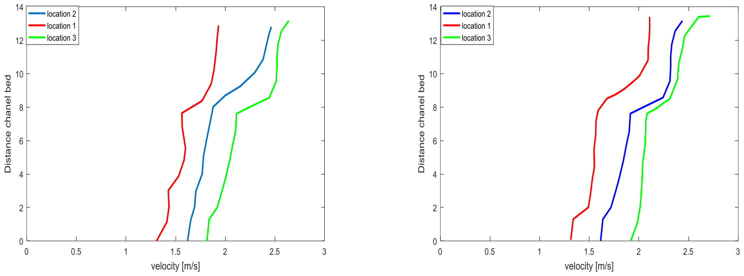
RESULTS

Velocity profiles

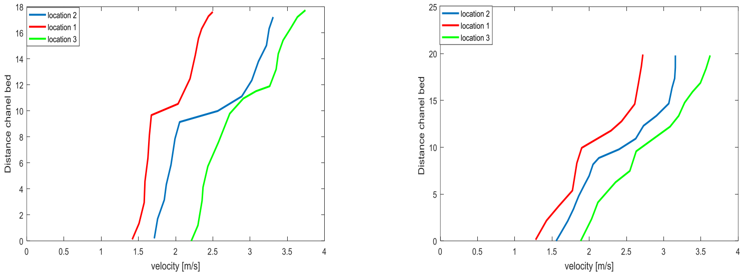
Velocity data in vegetation can be a key parameter for any studies. In this study, velocity data at different locations in the vegetation region and in different heights were measured by ADV in both emergent and submerged conditions. Measured velocities were used for showing velocity profiles and distribution.

In open channel flows, the velocity profile consists of two major layers: a near bed layer and an outer layer above. A near bed layer is the effect under different kinds of resistance forces such as drag induced by vegetation. Generally, it has been observed that the velocity is smaller in the stem layer of short vegetation compared with mixed layer vegetation or surface layer because the flow has more drag forces.

In the present study, the different flow depths were chosen in order to make the short dowels fully submerged and tall ones emergent. The velocity profiles of different flow depths are obtained, as shown in Figure 8, which show the velocity profiles of different layers of vegetation, and indicates that the velocity profile is mostly uniform and constant within the short vegetation and increases near the edge of short dowel, and then raises gradually till the surface of flow.



Velocity profile at h=12.6 Velocity profile at h=14.9



Velocity profile at h=17.3 Velocity profile at h=19.4

Figure 8. Velocity profiles in different locations and depths

It can be seen in Figure 8 that the trend of measured velocity data is not logarithmic, unlike that in open channel flows without vegetation.

Drag coefficient

The vegetation resistance is mainly induced by stems of vegetation and therefore most previous studies use circular cylinders to simulate the vegetation stems with different diameters (Stone and Shen, 2002; Armanini et al., 2005). It should be also noted that other parameters such as height thickness and density could affect the resistance of vegetation. To be as close as possible to the nature, circular dowels were built with different heights in our study.

Drag coefficient is one of the most important parameters, which could represent the resistance of vegetation. In this study the drag coefficient is computed by Equation 5:

$$C_d = \frac{g(1-\lambda l_{new}^{*})\pi d s}{2\lambda l_{new}^{*} v_c^2} \qquad (5)$$

Equation 5 has been used for single layer vegetation and shows a certain high accuracy. This equation with some modification is now used for double layer vegetation and the data have been tested by numerical data obtained from the modelling by Ansys Fluent. Various flow depths were used to cover both emergent and submerged flow conditions and the results are presented in Table 3.

Table3. Drag coefficient for vegetated channel in double layers condition.

Flow depth h(m)	C_D by Eq 5	C_D by Numerical modelling	C_D by Cheng and Nguyen (2011)
0.12	0.948	0.971	0.955
0.14	0.996	0.974	0.958
0.17	1.087	0.984	0.963
0.19	1.113	0.989	0.967

Table 3 indicates that when the short dowels are submerged and tall ones are emergent, the drag coefficient gradually increases as the increasing depth of flow. For example, C_D increases from 0.948 to 1.113 when the depth of flow increases from 0.12 to 0.19 m.

CONCLUSIONS

Experiments were undertaken in a 40cm-wide rectangular flume, which covered by circular cylinders of two heights to simulate the double layer vegetation under both submerged and emergent conditions in a flow depth. Along with the numerical modelling, the following findings may be drawn.

In contrast to open channel flows without vegetation, the hydraulic resistance like drag coefficient is dependent on depth of flow in open channel, submergence condition and different measurement location.

On the other hand, drag coefficient for mixed layer vegetation, is observed to increase with increasing flow depth, which shows that the resistance in lower density vegetation is less than high density one.

Flow velocity profiles show that the velocity of flow near the bed within the vegetation is considered as a single layer and is almost uniform and constant over different vertical distances. When the short vegetation is fully submerged and tall one is emergent the velocity profile becomes two staged and has a remarkable increase near the edge of short vegetation which followed by a gradual increase till the surface.

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