Impact of Partially Covered Vegetation on the Lateral Velocity Distribution of Open Channel Flow

[1]DEEPIKA PRIYADARSHINI PALAI, *Gandhi Institute of Excellent Technocrats, Bhubaneswar*
[2]PRASANTA DALABEHERA, *Capital Engineering College, Bhubaneswar, Odisha, India*

Abstract

The vegetation affects the flow process and water environment, thus drawing increasing attention to river environment management. Previous research is mainly focused on flow through vegetation in a channel with fully covered single-layer vegetation. However, in natural rivers, different heights' vegeta- tion often co-exists along one or two sides of a river. This paper experimen- tally studies how the flow velocity distribution is affected by the two differ- ent-layered vegetation allocated along two sides of an open-channel. The ve- getation was simulated by dowels of two heights, 10 cm and 20 cm, and ar- ranged in a parallel pattern along two sides of a flume under partially sub- merged conditions. The velocities along a cross-section were measured by Acoustic Doppler Velocimetry (ADV). The results of lateral velocity distribu- tion show that a strong shear layer exists between vegetation and non-vegetation zones, indicating the retarding effect of vegetation. Meanwhile, as the flow depth increases, the relative velocity in the free flow zone decreases compared with that in the vegetated region, indicating that vegetation resistance to the flow decreases as increasing depth under the same vegetation configuration. These findings would help understand the role of multi-layered vegetation inriparian management.

Keywords

Vegetated Flow, Double-Layer Vegetation, Velocity Profile, RiparianEnvironment

1. Introduction

Vegetation widely exists in natural rivers. Vegetation plays an important role in the river environment since the vegetation provides a suitable environment for habitat creation and biodiversity along with the improvement of water quality and reduction of bank erosion, and so on (Nepf & Ghisalberti, 2008; Greet et al., 2011; Zhang et al., 2020). Various types of vegetation grow along natural rivers, and sometimes they are planted for the purpose of engineering or ecological re- quirement (Chembolu et al., 2019). The riparian vegetation retards flow and in- creases the flow resistance caused by the additional drag from the vegetation. Consequently, the vegetation affects the velocity, Reynolds stress, and turbulence intensity (Nepf & Vivoni, 2000; Lopez & Garcia, 2001; Tang & Knight, 2001, 2009; Tang et al., 2010, 2011; Zhao & Huai, 2016; Tang, 2018, 2019a, 2019b).

Previous studies on vegetated flow were mainly on the velocity and resistance of flow (Carollo et al., 2002; Stone & Shen, 2002; Tang & Knight, 2009; Tang & Ali, 2013), where the single layer vegetation was simulated by artificial cylindric- al dowels of rigid or flexible type in laboratory flumes and in either emergent or submerged flow conditions (Tang et al., 2010, 2011; Yang et al., 2020; Yan et al., 2020). With the growing role of vegetation in the river ecological environment, much attention has been paid to understand the flow interactions with vegeta- tion and the physical processes at various scales (Curran & Hession, 2013; Nezu& Sanjou, 2008; Nepf, 2012).

The characteristics of flow through vegetation may be interpreted using dif- ferent mechanisms over the flow depth (Nikora et al., 2013; Huai et al., 2014; Rahami et al., 2020).Thus, the velocity profile can be modelled separately in a layer with each phenomenon described (Tang & Ali, 2013; Tang, 2018, 2019a, 2019b; Singh et al., 2019). The flow structure in vegetated channels has also been investigated through numerical modelling (e.g., Lopez & Garcia, 2001;

Neary, 2003; Zeng & Li, 2014) and CFD simulation using FLUENT (Souliotis & Prinos, 2011; Anjum et al., 2018; Anjum & Tasnka, 2019; Rahimi et al., 2019).

In riparian environments, there exists multiple-layered vegetation such as grasses, shrubs, trees. Shorter vegetation is often submerged while the tall vege- tation is emergent in high flow conditions. Thus, the flow structure becomes very complicated owing to the interaction between the flow and differ- ent-layered vegetation. To understand the influence of multiple-layered vegeta- tion on the flow structure, some laboratory studies were carried out in an open-channel with the bed fully covered by a mixing array of short and tall ve- getation (e.g., Liu et al., 2008; Anjum et al., 2018; Tang et al.. 2019; Rahimi et al.. 2019, 2020). Most recently, Tang et al. (2018, 2019, 2021) have conducted expe- riments on the flow with double-layer vegetation that covered one side of a channel bed. However, there is little study about the impact of non-evenly dis- tributed multi-layered vegetation along two sides of a channel, which commonly exists in rivers. This knowledge gap becomes the aim of this paper.

This paper presents the experimental results of lateral velocity distribution in an open channel: one side of the bed is covered with single-layered vegetation whilst the other side is with two-layered vegetation in a linear pattern. The ve- locities at different locations were measured by ADV (Acoustic Doppler Velo- cimetry), aiming at investigating how the vegetation affects the lateral velocity of flow when the short vegetation is under submerged and emergent conditions.

2. Experimental Setting

The experiment was conducted in the 20 m-long titling flume at XJTLU (Xi'an Jiaotong-Liverpool University). The flume has a rectangular cross-section of 0.4 m wide by 0.5 m high and is set at a bed slope (So) of 0.003. The vegetation was simulated by 6.35 mm circular plastic dowels in two heights of 10 and 20 cm, denoting the short and tall vegetation, respectively. Both the short and tall do- wels are arranged in a linear pattern with a spacing of 31.75 mm between the centres of dowels. The flume is sketched in **Figure 1**, where two different vegeta- tion arrangements are along two sides of the bed (see **Figure 2**). Only tall dowels are in vegetation region 1 (left), with the distance of the nearest dowel to wall A being 25.38 mm. In vegetation region 2 (right), there are two rows of short do- wels near the free region and two rows of tall dowels near wall B. Thus, each ve- getation zone has the same width as the free region, i.e., one-third of the channel width.

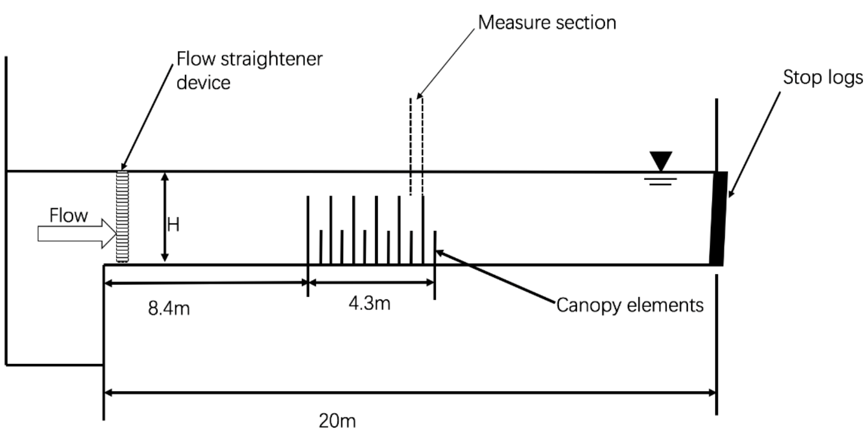


Figure 1. The sketch of the channel.

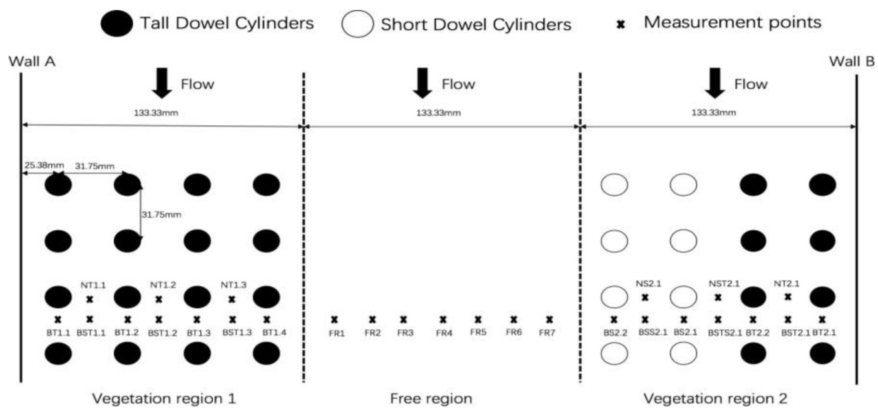


Figure 2. The arrangement of vegetation array and measurement locations.

The measured locations are coded as follows (see **Figure 2**): BT and BS denote the measurement locations behind the tall dowel and the short dowel, respec- tively, while FR denotes the free region (i.e., the central zone without vegeta- tion). The other notations are that BST = behind and side away from the tall dowel, NT = the location next to the tall dowel, NS = the location next to the short dowel, and NST = the location next to both short and tall dowels.

Two types of Nortek micro-ADV (downward- and side-probes) were used to measure velocity at various measurement locations in a cross-section. For most measurements, the downward-probe ADV was used to obtain 3D velocities in a vertical except for the 5 cm zone near the water surface, where the side-probe ADV was used instead. The sampling time of each measurement was set as 60 seconds. The WinADV software was used to process the velocity data of ADV. In the experiment, two flow depths of 9 and 14 cm were undertaken. The cor- responding discharge was 6.1 and 11.1 L/s, representing the following two flow conditions: all dowels are emergent, the short dowels are submerged while tall dowels are emergent.

3. Results and Discussion

In the subsequent figures, the velocity is normalized by the cross-sectional mean velocity U. The vertical distance (z) above the channel bed is normalized by theheight of short vegetation (h).

3.1. Lateral Change of Velocity Profiles

To understand the change of profiles in the different regions (the vegetation and non-vegetation region), the comparisons of velocity profiles at the representative locations (i.e., at locations BST, FR, BSS and BSTS) are shown in **Figure 3** and**Figure 4** for the cases of 9 cm and 14 cm, respectively.

Figure 3 and **Figure 4** clearly reveal that the velocities in the free region (FR)

are much higher than those in the vegetation region, indicating that the vegeta- tion has a considerably retarding effect on the velocity. Furthermore, in the emergent case (**Figure 3**), the velocity profiles are similar for various locations

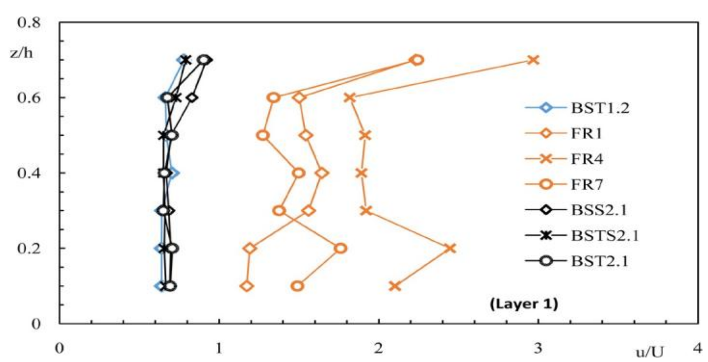
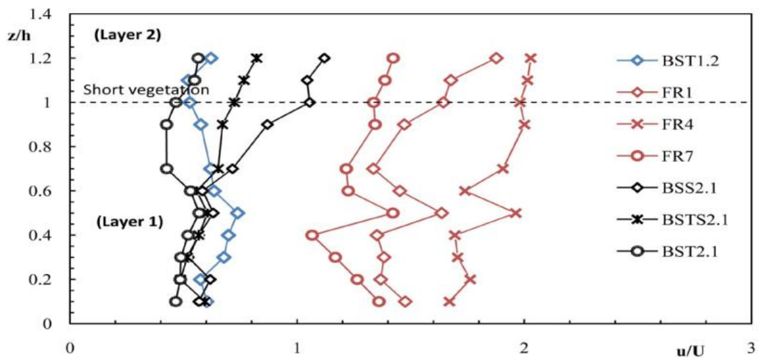


Figure 3. Lateral variation of velocity profiles for the flow depth of 9 cm.

Figure 4. Lateral change of velocity profiles for flow depth of 14 cm.

(BST, BSS and BSTS) within the vegetation region. However, the velocities tend to show some differences near the top of short vegetation depending on the lo- cations for the partially submerged case (**Figure 4**), where the velocity between short dowels (BSS) has the highest value while the velocity between tall dowels (BST) is the lowest. At the locations of BSS and BSTS (i.e. short vegetation in submerged conditions), their velocities start to increase from certain distances (z/h at about 0.6) below the top of short vegetation, indicating a penetration depth due to the strong shear between the upper free flow and lower vegetated flow (Nepf & Vivoni, 2000; Tang et al., 2021).



3.2. Lateral Distribution of Depth-Averaged Velocity

To show the impact of different vegetation configurations on the lateral distri- bution of velocity, the depth-averaged velocity (u_d) is calculated and shown in **Figure 5**, where y is the lateral distance from wall A. **Figure 5** shows that the depth-averaged velocity increases rapidly around the interface between the ve- getation region (1 or 2) and the free region. This implies that a strong momen- tum exchange occurs near the interface between the vegetation and no-vegetation regions. The large lateral velocity gradient at the interface is caused by the veloc- ity difference between the two regions, where the flow in the free region (i.e. center) is faster than that in the vegetation region where the slow-moving flow is due to the additional resistance of vegetation. These findings are similar to thoseobserved by Tang et al. (2019, 2021).

Besides, as the water depth increases, when the short vegetation is fully sub- merged but the tall vegetation is emergent (case H = 14 cm), the vegetation will reduce the relative velocity of the free region more than in the vegetation region, resulting in a smaller gradient of lateral velocity in the transition layer between the vegetation and non-vegetation regions. This result indicates that the influ- ence of depth on the resistance in the vegetated region is relatively smaller com-pared with that in the free region (Tang et al., 2019, 2021).

Further examination on the lateral velocity distribution of 14 cm case shows that the velocity gradient in the transition zone between the free region and re-gion 2 (i.e., two-layered vegetation) becomes larger than that between the free region and region 2 (tall vegetation). This effect may be due to the relatively in- creasing resistance of flow in the submerged short vegetation, which has addi- tional strong vertical mixing.

3.3. Discharge in Each Region

The discharge in each region can be calculated based on the lateral distribution of depth-averaged velocity. **Figure 6** shows the percentage of discharge in each region for the two cases. The discharge in the free region is about 61% - 63.5% of the total discharge, where it is nearly the same for each vegetation region, al- though the free region takes only one third of the channel width. With increas- ing water depth, the discharge percentage in the free region slightly decreases whereas it increases in both vegetation regions. This result may be caused by the relative submergence of vegetation, because of reduced resistance from the short vegetation in region 2 changes from emergent to submerged condition when flow depth changes from 9 cm to 14 cm.

In general, the discharge percentage through the entire vegetation region slightly increases from 39% to 37% as the depth of flow increases from 9 cm to14 cm, i.e. from the emergent to partially submerged conditions.

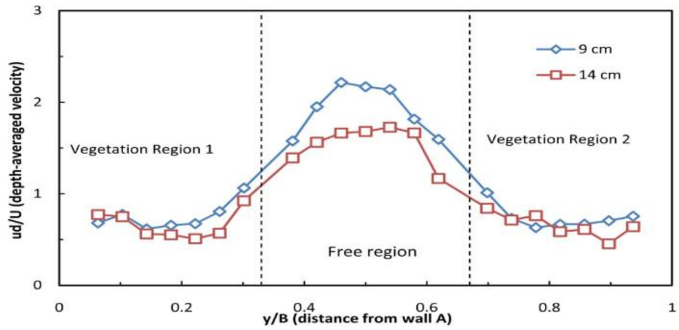


Figure 5. Lateral distribution of depth-averaged velocity u_d (B = 40 cm).

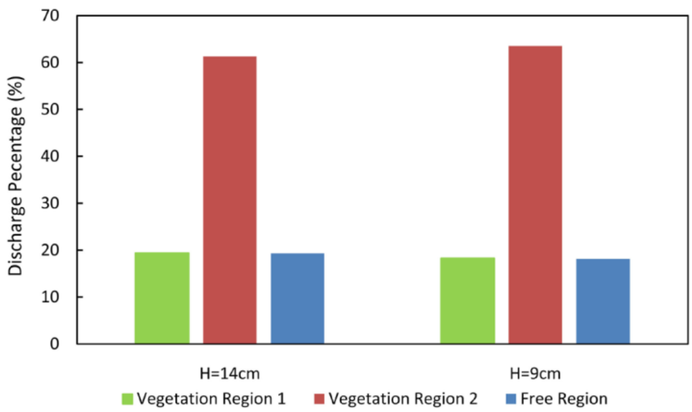


Figure 6. Discharge percentage in each region for three flow depths: 9 cm and 14 cm.

4. Conclusion

Based on the novel experimental study on the open-channel with two bedsides covered with different vegetation patterns, the results show that the vegetation pattern will affect the lateral velocity distribution. The following points may bedrawn:

- The velocity profiles are different laterally. The velocity profiles in the free region are much higher than those in vegetated regions. Although the vertical variation of velocity in all regions is small in the emergent conditions, the velocity starts to increase from a certain distance below the top of short vegetation when the flow depth increases to make the short vegetation under submergence.
- The depth-averaged velocities in the free region are much larger than in the vegetation regions, indicating that a strong momentum exchange exists be- tween the vegetation and non-vegetation regions and that the presence of thevegetation has a noticeably retaining effect on the flow.
- As the flow depth increases, the vegetation will reduce the relative velocity in the free region more than in the vegetation region, resulting in a smaller gra- dient of lateral velocity in the transition layer between the vegetation and non-vegetation regions.
- In the free region, the velocity near its center is much larger than that near

the vegetation regions.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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