Velocity Profile and Lateral Distribution in an Open Channel with Two Distinct Vegetative Zones

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Abstract: Riparian vegetation has drawn increasing attention because it plays a vital role in the ecological environment and flow process in river systems. Previous literature on vegetative flow mostly focuses on understanding the hydraulic feature of uniform single-layered vegetation in a channel. In many rivers, vegetation often grows unevenly along riversides, on which very few studies have been done. For understanding the effect of unevenly distributed vegetation on the flow, this paper presents novel experimental results in an open channel with each side of the bed occupied by different height vegetation. The vegetation was mimicked by dowels 10 cm and 20 cm high and in two flow conditions: fully and partially submerged. A micro ADV (Acoustic Doppler Velocimetry) was used to measure 3D velocities at various positions. Observed data show that the averaged velocity profile in the non-vegetative region (free-flow zone) is influenced by neighboring vegetative regions, where the velocity reflects at some distance below the top of vegetation. A large lateral velocity gradient exists near the interfacial boundary between vegetative and non-vegetative flow regions, indicating that a transition layer occurs near the interfacial boundary owing to the momentum exchange. Moreover, with the increasing flow depth, the zonal velocity in the non-vegetative region decreases slightly while the zonal velocity increases accordingly in the vegetative region (either short or tall vegetation sub-region), indicating that the averaged velocity in the vegetative region is affected by the submergence of vegetation. These findings on the channel flow with unevenly layered vegetation would benefit riparian management and the design of ecological and habitat zones in terms of the width and height of vegetation.

1 INTRODUCTION

Riparian vegetation plays a vital role in the water environment and ecologic systems of rivers. Vegetation creates a place of habitat with rich biodiversity for aquatic animals and birds, enhances water quality, and prevents the erosion of river banks and beds. In natural rivers, different types of vegetation grow on the riverside. In practice, vegetation is intentionally planted for ecological purposes or engineering requirements. In the watercourse, riparian vegetation interacts with the flow and affects the hydraulic features of flow (Ghisalberti & Nepf, 2006). The existence of vegetation induces additional flow resistance to flows because of the drag force of vegetation (Stone & Shen, 2002), thus altering the velocity and turbulence structure of flow (Lopz & Garcia, 2001; Nezu & Sanjou, 2008; Yang et al., 2015; Tang et al., 2021c).

In the literature, many studies have been undertaken on the mean velocity of flow and the flow resistance with one-layered vegetation, which is considered rigid or flexible in either submerged or emergent conditions (Aberle & Jarvela, 2013; Cheng, 2011; Yang et al., 2020; D'Ippolito et al., 2021). Vegetation in laboratory studies was mostly mimicked by artificial vegetation, either rigid or flexible (Cheng, 2011; Yang et al., 2020). Considering the significant role of vegetation in the river system, researchers have drawn great interest in understanding vegetation's impact on the sediment transport and hydraulics of flows at different scales (Curran & Hession, 2013; Chembolu et al., 2019).

The flow interaction with vegetation is complex. The flow mechanism of vegetation in limited depths has been interpreted (Okamoto & Nezu, 2013; Nikora et al., 2013; Hui et al., 2014; Rahimi et al., 2020c), resulting in various analytical models for predicting the velocity profile (Nepf, 2012; Tang, 2019a, 2019b) and the lateral variation of depth-averaged velocity (Tang & Knight, 2009; Tang et al. 2010, 2011). Moreover, numerical solutions have been made to

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understand the hydrodynamics of vegetated flows through numerical models (e.g. Neary, 2003; Stoesser et al. 2010) and CFD modelling using Ansys FLUENT (Rahimi et al., 2020 a&b; Anjum & Tanaka, 2019; Anjum et al., 2018).

In natural rivers, different types of riparian vegetation co-exist, such as trees, shrubs, grasses. Tall vegetation is usually emergent whilst short vegetation is submerged. The flow through different height vegetation has a complex flow structure. Recently, some investigators have studied the open channel flow with the entire bed occupied with combined tall and short vegetation, so-called doubly or two-layered vegetation (e.g., Rahimi et al., 2020c; Singh et al., 2019; Hui et al., 2014; Liu et al., 2008). Recently, Tang et al. (2019, 2021d) also experimentally investigated the impact of partial two-layered vegetation on the velocity and turbulent structure of the flow. However, very little research has been performed to understand the impact of vegetation unevenly distributed over each side of a channel bed, which often occurs in natural rivers.

In this paper, a novel experiment of vegetative flow was taken in a tilting water flume. The two sides of the flume bed were occupied by different layers of vegetation: one side in one layer, the other in two layers. 3D velocity at various locations along a section was measured using ADV (Acoustic Doppler Velocimetry) to understand the flow characteristics in the regions with and without vegetation. This paper presents averaged velocity in three different zones under partially and fully submerged conditions.

2 EXPERIMENTAL SETTING

The experiment was performed in the 20*m* long titling flume of hydraulics laboratory at Xián Jiaotong-Liverpool University (XJTLU). This rectangular flume, 0.4*m* (wide) x 0.5*m* (high), was adjusted at a bottom slope (*S*) in 0.003 (Figure 1) (Tang & Hu, 2021). The rigid vegetation was mimicked by PVC cylindrical dowels of 6.35 *mm* in diameter, with two heights of 0.2 *m* (tall) and 0.1*m* (short). A pre-perforated PVC plate of 10 mm thick is laid on the flume bed to hold the dowels. As shown in Figure 1, the 4.3*m*-long vegetative session begins 8.4*m* away from the channel entrance and has a distinct pattern of vegetation on two sides of the bed (see Figure 2) (Tang et al., 2021a). Tall dowels are on the left side (vegetation region 1), while on the right side (vegetation region 2) of the flume, tall dowels in two rows are close to wall B, along with short dowels in two rows near the free region in the center. All dowels were linearly distributed with 31.75 *mm* apart between the dowels. Therefore, the width of the free region and each vegetation region is the same, equal to one-third of the bed width.

Due to the limitation of accessible area, two types of Nortek micro ADV (downward and sideward) were used for measuring velocity at different positions at a cross-section. The downward ADV was mainly used to measure most 3D velocities in a depth except close to the water surface, where the velocity was obtained by the sideward ADV, which was able to measure the velocity close to the water surface. 60 seconds were set as the sampling time for each measurement. To ensure reliable data, SNR (signal-to-noise ratio) and correlation coefficient during the measurement should maintain at least 10 and 70%, respectively. The velocity data obtained by ADV was then processed using WinADV software. The experiment was undertaken in three flow depths: 9, 14 and 22 *cm*. The corresponding flow rate is 6.1, 11.1 and 19.49 *l/s*, which respectively denotes the following conditions: emergent (all dowels non-submerged), partial submerged (only short dowels submerged), and fully submerged (all dowels fully submerged).

The measuring positions are shown in Figure 2 and coded as follows: BT and BS respectively denote the measuring positions behind the tall and short dowels, whereas FR means in the free region (i.e., the non-vegetative central area). Other notations include that BST and BSS are denoted as behind and side away from tall and short dowels, NT denotes the position next to tall dowels, NS represents the position next to short dowels, and NST is the location next to the short and tall dowels.

For the effective comparison, in the figures of the subsequent section, the height of the short dowel (*h*) is used to normalize the vertical distance (*z*) above the flume bottom, whereas the cross-sectional average velocity *U* is normalized velocities.

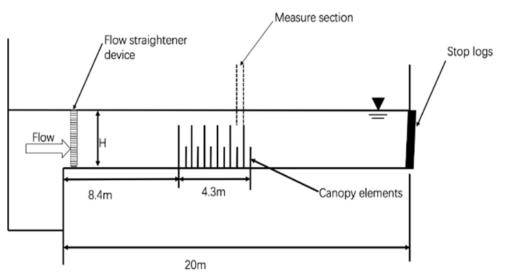

Figure 1: The sketch of the experimental channel.

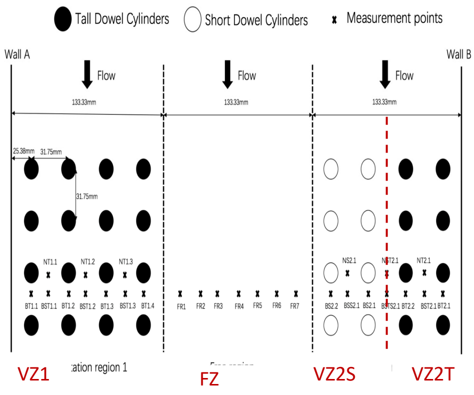

Figure 2: The layout of dowels and measurement points in the experiment.

3 VELOCITY RESULTS

3.1 Averaged Velocity Profiles

The lateral variation of velocity profiles at different locations (e.g., BS, BT, BST) has been reported in Tang & Hu (2021). To obtain a broad view of velocity profiles in each subzone, the averaged velocity is calculated to reveal its variation, as given in Figures 3-4 for the two experimental depths: partially submerged flow (H= 14 *cm*) and fully submerged flow (H = 22 *cm*).

In the partially submerged flow (Figure 3), the observed result reveals that the averaged velocity profile in the free zone (FZ) is significantly larger than those in the vegetated zone (VZ1 and VZ2). This result suggests that the vegetation decreases the water velocity. Compared with VZ1 and VZ2T, the averaged velocity in VZ2T is smaller than that in VZ1 despite the same type of tall vegetation, showing that the effect of velocity of neighbouring zone: The large velocity in VZ1 is caused by the higher velocity of neighbouring zone (FZ) compared with the smaller velocity in VZ2T due to small velocity in the neighouring zone (VZ2S). This effect also explains the moderated velocity profile in VZ2S, which is between the highest velocity zone FZ and the smallest velocity zone VZ2T. Furthermore, the vertical variation of averaged velocity is different depending on whether the vegetation is submerged or not. The velocity remains nearly constant in emergent conditions (VZ1 and VZ2T), where the velocity begins to increase from some distance above the bed until to the water surface for both the free flow zone (FZ) and short vegetation zone (VZ2S). It is noticed that the velocity in VZS2 has a reflecting point near the top of short vegetation, but the velocity in FZ does not have. The reflecting point of velocity in submerged conditions has also been observed in the literature (Yang et al., 2015; Tang et al. 2021b).

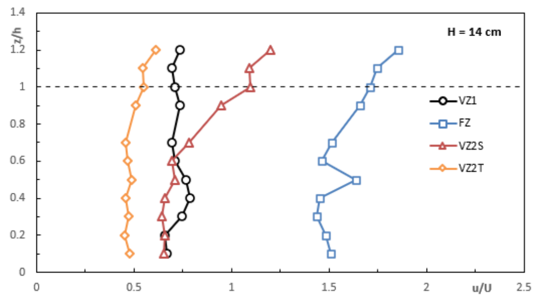

Figure 3: Averaged velocity profiles for H=14 *cm*.

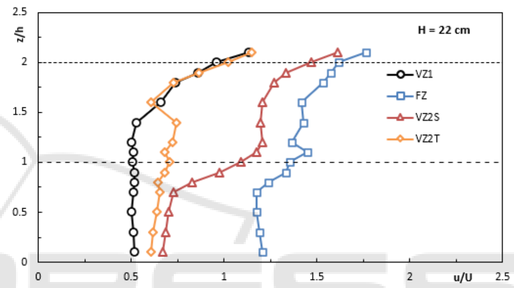

Figure 4: Averaged velocity profiles for H= 22 *cm*.

In the fully submerged flow (Figure 4), the observed averaged velocity profiles are similar to those in the partially submerged flow. This is that the averaged velocity profile in the free flow zone (FZ) is significantly larger than those in the tall vegetated zone (VZ1 and VZ2T), while the velocity profile in the short vegetation zone (VZ2S) lies between those in the free zone and tall vegetation zone (VZ1 and VZ2T). This result confirms that the vegetation dramatically reduces the velocity of flow due to the additional drag force caused by vegetation. In a close comparison between VZ1 and VZ2T, the averaged velocity in VZ2T is larger than that in VZ1 in the low depth (about z/h < 1.6), but they are almost the same in the upper layer close to the water surface (z/h >1.6), showing that the velocity of neighbouring zone affects the flow in the low layer near the bed, but has a limited impact on the flow of the upper layer close to the surface. This result demonstrates that the different impact of the neighboring zone on the flow of tall vegetation zone exists between the fully and partially submerged flow conditions.

In the fully submerged flow, the averaged velocity profile in the short vegetation zone (VZ2S) shows an ‘S-type’ profile, indicating that the velocity has three inflecting points: two near the top of short vegetation and one near the edge of tall vegetation, which was also showed by Rahimi et al. (2020c) and Huai et al. (2014).

Furthermore, it was found that there exists an almost constant velocity layer near the bed, depending on the submergence. The height of the constant velocity layer is about 1.5h for the tall vegetation zones (VZ1 and VZ2T), whereas its height is about 0.75h for the short vegetation zone (VZ2S). This result is well consistent, showing that the constant velocity starts to increase at the point below 0.25 height of the vegetation. This point is the first reflecting point of velocity, mainly affected by the penetration of surface flow, as obtained by many researchers (Nepf. 2012; Tang et al. 2021d). Meanwhile, it should be noted that the vegetation affects the vertical distribution of velocity in the free zone (FZ), which does not follow the logarithm of velocity in open-channel flow.

3.2 Lateral Variation of Depth-mean Velocity

To study how the vegetation affects the lateral variation of velocity, the depth-mean velocity (U_d) was computed and presented in Figure 5. In general, Figure 5 shows that large velocities occur in the central free zone and decreases from the centre of the free zone to either edge of the vegetated zone. It was observed that a large velocity gradient occurs around either the interface between the non-vegetative zone (FZ) and vegetative zone (VZ1 and VZ2S). This result implies that there exists extensive momentum exchange around the interface between FZ and VZ zones, which is caused by the large velocity difference. This finding is similar to the results observed by Tang et al. (2021b & c).

In addition, as the water depth increases, the vegetation from partially submerged (H=14cm) to fully submerged (H=22cm) affects the lateral variation of velocity. Compared with the partially submerged condition, the lateral velocity gradient around the interface is relatively smaller, revealing that the vegetation causes a relatively small difference in velocity between vegetative and non-vegetative zones as increasing flow depth. This implies that the vegetation causes relatively large additional flow resistance in the emergent or partially submerged condition than the fully submerged condition.

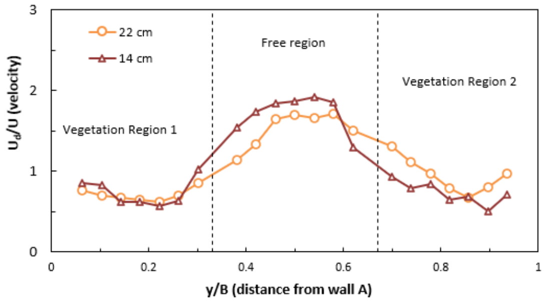

Figure 5: Lateral variation of depth-mean velocity (B = 40 cm).

3.3 Zonal Velocity in Different Zones

The averaged velocity of each region, called zonal velocity (Ui), can be obtained from the lateral distribution of depth-mean velocity (Figure 5). The obtained zonal velocity at each region is shown in Figure 6, which includes three flow depths. Figure 6 shows that the highest zonal velocity occurs in the free flow zone, the lowest zonal velocity occurs in the zone of tall vegetation, and the zone of short vegetation (2S) has the modest zonal velocity. This result is as expected that the more vegetation, the smaller the velocity becomes. The relative size of zonal velocity in each zone will change depending on the submergence of vegetation. In the emergent case (H=9 cm), the zonal velocity in the free flow zone is almost 1.7 times of the cross-sectional velocity (U), i.e. almost 70% higher than U, whereas the zonal velocity in vegetated region 1 is about 0.7 times of U, i.e. 30% smaller than U, and a similar velocity occurs in vegetation region 2, which is equivalent to region 1 on average. As depth increases, the zonal velocity in the free region becomes relatively smaller while the zonal velocity in vegetation 2 increase accordingly, although the zonal velocity in vegetation 1 does not change very much. To be detailed, the zonal velocity in the free flow zone decreases from 1.6U to 1.46U when the flow depth (H) rises from 14 cm (partially submerged case) to 22 cm (fully submerged case), while the zonal velocity increases from 0.57U to 0.78U in tall vegetation zone (2T) and from 0.85U to 1.07U in short vegetation zone (2S). This result reveals the effect of the vegetation submergence on the zonal velocity: larger submergence of vegetation leads to a higher zonal velocity due to relatively smaller flow resistance inserted.

In addition, because the discharge is the product of the velocity and area, a large zonal velocity corresponds to a large discharge for the same sized region. The zonal velocity in Figure 6 implies that:

(1) for a given depth, the free region carries out a higher portion of discharge compared with that in the same sized vegetation zone; (2) the short vegetation zone (2S) has more flows than the same sized tall vegetation zone (2T), which is enhanced particularly with the increasing submergence of vegetation.

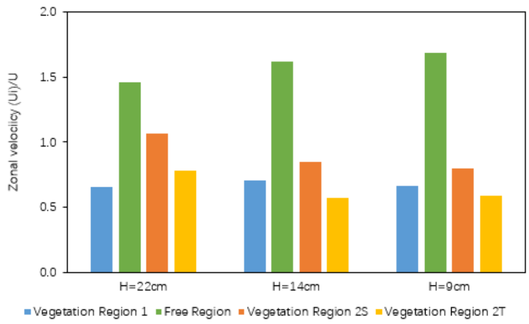

Figure 6: Comparison of zonal velocity in each region.

4 CONCLUSIONS

The impact of the height and distribution region of vegetation on the open-channel flow has been investigated through experiments with two distinct conditions. The observed results show that the averaged velocity in each zone is affected by the distribution/pattern and submergence of vegetation. A few points may be drawn as follows:

1) The averaged velocity profile in the non-vegetative zone (FZ) is much larger than that in the vegetative zone, showing retarding effect of vegetation. The velocity profile of the fully submerged flow has shown significant reflecting points depending on the submergence of vegetation: the height of reflecting velocity occurs about z/h=1.5 for tall vegetation zone, while the reflecting velocity happens at about z/h=0.75,1.15 and 1.80, as an 'S-type' profile.
2) The averaged velocity profile in the non-vegetated zone (FZ) shows a constant value in a layer near the bottom, and it does not follow the logarithm law.
3) There exists a great lateral momentum exchange in a layer along the interfacial boundary between vegetative and non-vegetative regions, showing a large lateral velocity gradient near the interface. This gradient becomes smaller as increasing flow depths when the flow changes from partially submerged to fully submerged condition.
4) The zonal velocity of each region is affected by the submergence of vegetation. With increasing flow depth, the status of vegetation changes from emergent, partially submerged to fully submerged conditions, the zonal velocity in the free region becomes slightly smaller, but the zonal velocity in vegetation region 2 (either short or tall vegetation sub-region) increase accordingly. This result will help practitioners in the planning and management of vegetated channels.

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