Proceedings of the 39th IAHR World Congress
19–24 June 2022, Granada, Spain
doi://10.3850/IAHR-39WC2521716X2022133

Effect of Multiple Layered Vegetation on the Velocity Distribution of Flow in An Open Channel

Xiaonan Tang*, Suyang Zhang, Jiaze Cao, Hanyi Wang, Nanyu Xiao, Yutong Guan

Xi'an Jiaotong-Liverpool University, Suzhou, China
e-mail: Xiao.Tang@xjtlu.edu.cn

Abstract

Vegetation of various heights widely co-exists in natural rivers and wetlands, where the ecological environment and flow process are affected by the riparian vegetation, which has drawn great attention in river engineering and aquatic environmental management. The majority of studies in the past have been mainly focused on the understanding of flow through single-layered vegetation. However, in natural riverine environments, vegetation with different heights often co-occurs in natural rivers, which have a different effect on the flow than the single-layered vegetation. In this paper, a novel experiment was designed to study the flow characteristics in an open-channel with vegetation of three different heights on the channel bed. Experiments were conducted in partially submerged conditions to understand the effect of the vegetation on the velocity distribution. Three heights of dowels, 10, 15 and 20 cm, were used to mimic rigid vegetation in a staggered pattern for each type of dowel. Velocities at various locations in a section behind the vegetation row were measured by mini propeller velocimetry. Experimental results showed that the vertical velocity distribution is affected by vegetation heights, revealing a distinct vertical distribution of velocity between and behind the vegetation. No matter the position, all vertical velocity profiles are almost constant from the bed to a certain distance of about 3/4 short vegetation height and then increase to near the top of short vegetation, where a velocity reflection occurs. Afterward, the velocity continues to increase rapidly to the water surface. Generally, the velocity profile behind the short vegetation zone is much larger than directly behind the vegetation. Also, the streamwise velocities behind the short and tall vegetation are smaller than those behind the median and short vegetation zone. These findings on the flow with multiple layered vegetation would be helpful for riparian management practices to maintain healthy ecological and habitat zones.

Keywords: Vegetated flow; Multiple-layered vegetation; Aquatic environment; Velocity; Open-channel

1. INTRODUCTION

Vegetation widely exists in natural watercourses or associated floodplains. It becomes an important part of the river ecosystem since the vegetation creates an ecological environment for habitat and biodiversity, improves water quality and protects bank erosion. Various types of vegetation grow in the lowland river environment, and they often are deliberately planted for the demand of engineering or environment. Vegetation in the watercourse largely affects the flow structure (Nezu & Sanjou, 2008; Caroppi, et al., 2020; Nepf, 2012). As an additional source of flow resistance in the channel, vegetation has been shown to reduce bulk flow velocity and discharge (Lopez & Garcia 2001; Carollo et al. 2002, Stone & Shen, 2002; Yang et al. 2020), and Reynolds stress and turbulence intensity (Ghisalberti and Nepf, 2002, 2006; Chen et al. 2010; Chembolu et al. 2019). Consequently, it alters sediment transport processes (Lopez & Garcia 1998; Curran & Hession 2013) and increases habitat diversity (Naiman et al. 1993). Therefore, understanding the characteristics of flow through and around vegetation is essential to managing the river system.

As a prerequisite, the velocity and resistance of flow through single-layered vegetation have been widely studied (Carollo et al. 2002; Stone et al. 2002; Tang & Ali, 2013, 2019b; Yang et al. 2020), where the same height vegetation was modelled by artificial cylindrical dowels for rigid type in laboratory flumes and under either emergent or submerged flow conditions. For the flow with emergent vegetation, the velocity remains almost constant over the depth, but the velocity shows a distinct profile within and above the vegetation in the flow of submerged vegetation, where the velocity profile can be described by two-layered models (Tang & Ali, 2013; Nikora et al. 2013; Tang, 2019 a&b; Singh et al. 2019). In recent years, the flow characteristics through vegetation in open channels have also been studied through numerical models (e.g. Neary, 2003; Tang et al. 2021b) and numerical simulation using FLUENT (Souliotis & Prinos, 2011; Anjum & Tanaka, 2019; Rahimi et al. 2019).

In natural riparian environments, various types of vegetation (e.g. grasses, shrubs and trees) co-exist. Shorter vegetation is often submerged while the tall vegetation is emergent in certain flood flow conditions. To understand how the vegetation of differential heights affects the flow structure, some experimental studies have been undertaken on the channel with an array of short and tall vegetation together, so-called double or two-layered vegetation (e.g. Liu et al. 2008; Huai et al. 2014; Anjum et al., 2018; Tang et al. 2018; Rahimi et al. 2020). These studies show that the velocity profiles are largely different from the flow through single-layered vegetation. To further study the effect of multiple-layered vegetation on the flow, the present paper presents a novel experimental study to explore the velocity variation of the channel with three-layered vegetation, which more commonly exists in rivers.

In this study, a novel experiment of mixing vegetation of three heights has been set up in a tilting flume under the flow condition that short and median height vegetation was submerged while the tall vegetation was emergent. The velocities at different locations in a section behind the vegetation row were measured by propeller velocimetry, which aims at investigating the variation of flow velocity behind vegetation.

2. EXPERIMENTS AND MATERIAL

The experiments were undertaken at XJTLU (Xián Jiaotong-Liverpool University) in the titling water flume of 0.4 m wide and 0.5 m high rectangular cross-section, which was set at a bed slope of 0.003. The flume is sketched in Figure 1, which has a 4.3 m long vegetation session starting 8.4m from the flume entrance, as described elsewhere (Tang & Hu, 2021). The vegetation was mimicked by circular plastic dowels of 6.35 mm in diameter, whose heights are 0.1, 0.15 and 0.2 m, representing the short, median and tall vegetation, respectively. Both the median and tall dowels are arranged in a linear pattern while the short dowels are staggered, with the spacing interval between dowels being 31.75 mm. The dowels were amounted into a 10 mm thick pre-perforated PVC plate placed on the bed of the flume (Figure 2). The first and last row of the dowel is 25.38 mm away from the wall.

A mini propeller velocimetry was used to measure streamwise velocity at different measurement locations 1-12, as shown in Figure 2. In our experiment, the flow depth of 17cm was set up with the corresponding discharge being 17.55 l/s, which denotes that both short and median vegetation were submerged while tall dowels were emergent. At each position, velocity was measured at 16 points in a vertical to capture the vertical distribution, whereas the velocity value at each measuring point was the mean value of a sampling time of 20s by the propeller velocimetry (10s as suggested in the manual), which was reliable after several pre-tests.

In the subsequent figures in the Results and Discussion section, the vertical distance (z) above the channel bottom is normalized by the height of short dowel (h), whereas velocities are normalized by the frictional shear velocity u*. The measured locations are coded as follows (see Figure 2): P1, P5 and P9 (P denotes the position) are directly behind the short and tall vegetation; P3, P7 and P11 are directly behind the median and short vegetation, whereas the test points of even number (P2, 4, 6, 6, 8, 10, 12) denote the measurement locations behind the gap of short and median vegetation. Note that P12 is at the central line of the channel and the lateral distribution of vegetation along the central line (P12) is not symmetric.

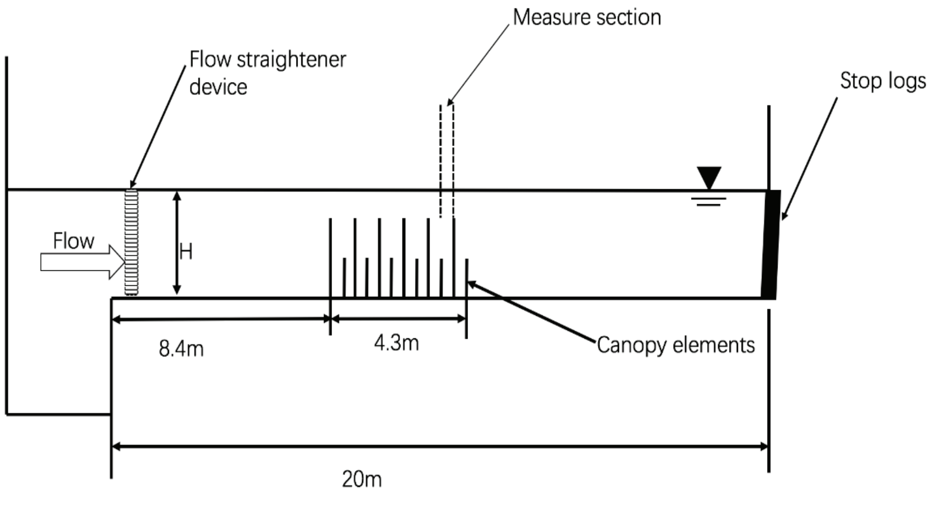

Figure 1. The sketch of the experimental channel.

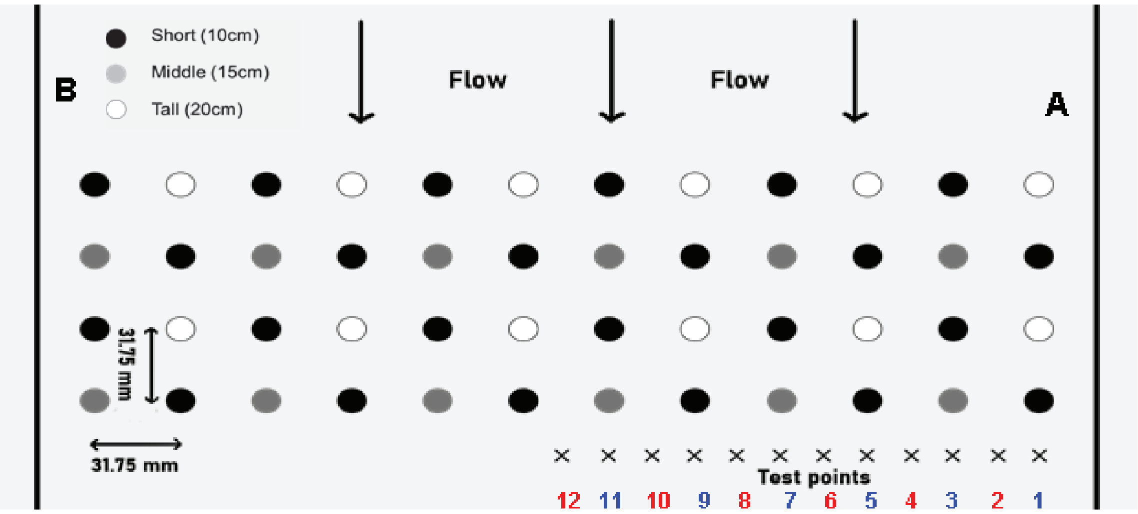

Figure 2. The layout of vegetation array and measurement locations in the experiment.

3. RESULTS AND DISCUSSION

3.1 Velocity Profiles Directly Behind Vegetation

To identify the effect of different distributions of vegetation, the comparison of velocity profiles behind the same pattern of vegetation was made. Figure 3 shows velocities at the locations directly behind the vegetation (i.e. at locations P1, 3, 5, 7, 9 and 11). Actually, the locations of P1, 5 and 9 are at the same position (group 1), i.e. directly behind the short after tall vegetation; whereas the locations of P3, 7 and 11 are at the same position (group 2), i.e. directly behind the median after short vegetation. In general, the velocity is almost constant near the bed ($z/h < 0.75$), and then increases until the top of short vegetation, where the velocity has a reflection: The velocity has little variation in the layer above $z=h$ for group 1, but the velocity has a small increase to the middle way of layer 2 and then rapidly increases to the water surface for group 2. The distinct velocity profiles above $z=h$ indicate the different effects of the upstream vegetation. The velocity profile in group 1 shows a typical velocity vertical distribution of double-layered vegetation flow, given by Rahimi et al. (2020), because the velocity beyond $z=h$ in group 1 is still in the protecting zone of tall vegetation upstream, whereas the velocity above $z=h$ in group 2 is like a free surface flow, which is not affected by the short vegetation upstream.

Close comparison on the velocity profiles in group1 (P1, 5, 7) shows that the wall has certain impact on the velocity: the closer to the wall, the smaller the velocity in the zone above the short vegetation ($z > h$); however, the velocity near the wall (P1) is larger than those (P5 & 9) away from the wall for the zone below the short vegetation ($z < h$). Among the velocities in group 2, the velocity (P11) close to the center of the channel is larger than those (P3 & 7) away from the center in the majority of flow depth ($z/h < 1.3$), whereas the velocity at P7 becomes the largest near the water surface.

3.2 Velocity Profiles Behind the Gap of Vegetation

To identify the lateral variation of velocity profiles behind the gap of vegetation (i.e., the velocity profiles at locations P2, 4, 6, 8, 10 and 12), the comparison of their velocity profiles is given in Figure 4. In terms of the position behind the same two types of vegetation upstream, the locations of P2, 6 and 10 are at the same position (termed group 3), i.e. at the center of gaps behind short and median vegetation (away from wall A). The locations of P4, 8 and 12 are at the same position (group 4), i.e. at the gap center behind median and short vegetation. Overall, the velocities at P6 and 10 are almost the same; they are larger than the velocity profile at P2, particularly at the upper layer near the surface ($z/h > 1.25$), indicating the effect of the boundary wall on the velocity at P2, which is smaller than the velocities at the positions far away from the wall. The boundary effect of the wall also applies for the velocity profiles in group 4, that is, the far the position away from the wall (wall A), the larger the velocity, e.g. P8 > P4, especially in the layers above $z=h$. However, interestingly note that the velocity profile at P12 (the center of the channel) becomes smaller than any other profile at a lower layer ($z/h < 1.25$), but its velocity in the upper layer lies between P4 and P8. This could be explained by the effect of an asymmetric distribution pattern of vegetation in a cross-section.

Compared with the velocity profiles behind the vegetation (Fig.3), the velocity profiles at the gaps behind the vegetation (Fig.4) are similar in the bottom layer (layer 1, $z/h \leq 1$): almost constant near the bed ($z/h <$

0.75), and increases rapidly until the top of short vegetation, where the velocity has a reflection. Generally, the velocities beyond z/h=1 increase as the increasing depth at a relatively moderate pace than those in group 2 in Figure 3, showing the combined effect of both short and median vegetation.

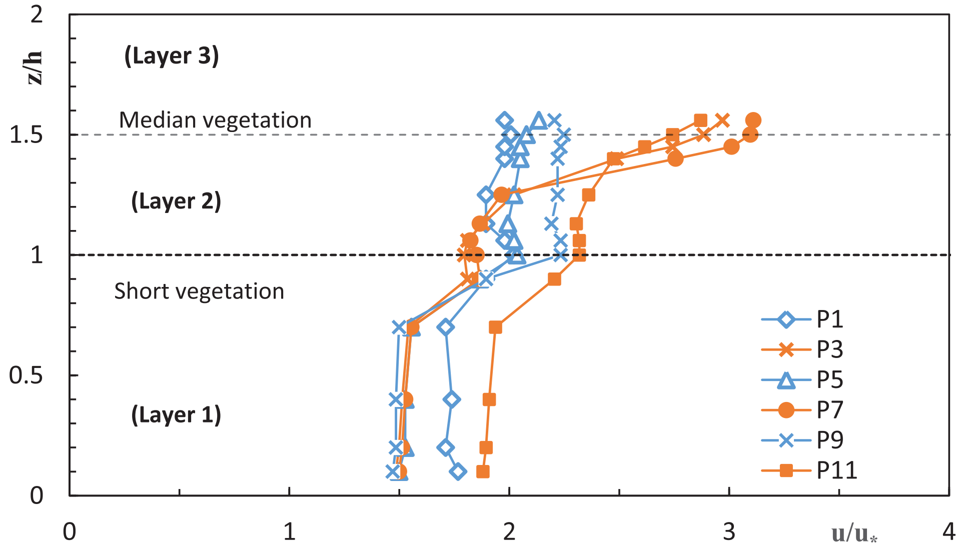

Figure 3. Velocity profiles directly behind the vegetation at the flow depth of 17 cm.

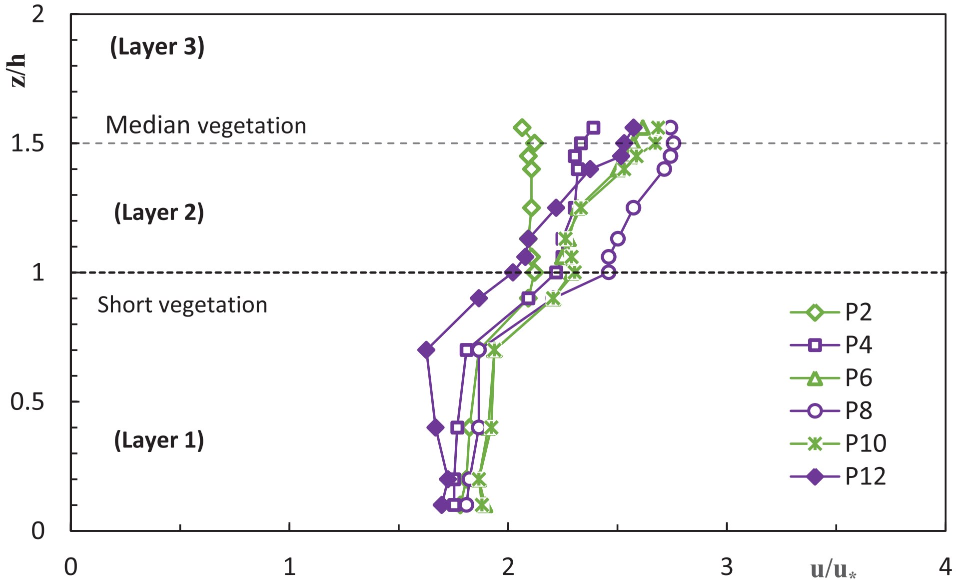

Figure 4. Velocity profiles behind the gap of vegetation at the flow depth of 17cm.

3.3 Comparison of Velocity Profiles at Various Positions Behind Vegetation

To illustrate the influence of vegetation on the velocity profiles at various positions behind the vegetation, Figure 5 shows the comparison of velocity profiles at the locations far away from the wall (at P6-10), where the wall is assumed to have negligible effect. Figure 5 clearly shows that: (a) In the lower layer (layer 1, z/h <1), the velocities have a similar pattern of variation: the velocity is almost constant near the bottom (z/h < 0.75) and then steadily increases from 0.75h to the top of short vegetation, and the velocity behind the gap is larger than the one directly behind the vegetation. (b) In the upper layer (z/h > 1), the velocity continuously increases up to the water surface, depending on the positions behind the vegetation. Obviously, in the upper layer the velocity directly behind vegetation is greatly affected by the vegetation height, where the velocity varies small at P9 but largely at P7. This can be explained that the small velocity change at P9 is caused by the tall vegetation upstream, while the velocity at P7 is not affected by the short vegetation upstream in the upper layer. It is not surprising that the velocity at gaps (P6, 8, 10) in the upper layer does not change dramatically because they are in the region with a combined impact by all three types of vegetation.

Overall, the velocity is larger behind the gap of vegetation (P6, 8, 10) than directly behind the vegetation (P7 and 9), except near the water surface.

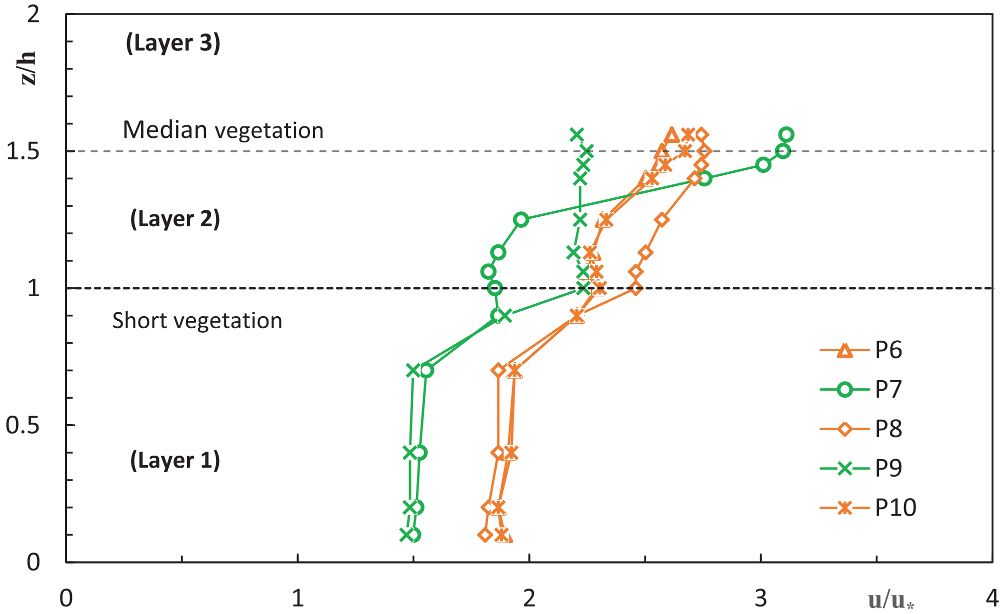

Figure 5. Comparison of velocity profiles at various positions behind the vegetation.

3.4 Averaged Velocity Profiles at Some Typical Positions

In previous sections, we have compared the velocity profile changes at different positions in great detail. To reveal the change of average velocity profiles at some typical locations, Figure 6 compared the averaged profiles at the same position related to the combined effect of a group vegetation. In Figure 6, BST denotes the averaged profiles at P1, 5, 9 (directly behind the short and tall vegetation), BMS represents the average at P3, 7, 11 (directly behind the media and short vegetation). In contrast, SM denotes the average at all positions at P2, 4, 6, 8, 10 (behind the gaps of short and median vegetation).

Figure 6 shows a distinct difference of the averaged velocity profiles at some typical positions (BST, BMS and SM): In the lower layer (layer 1, z/h < 1), the averaged velocity shows a ‘⌠’ type of profile, i.e. the velocity varies small near the bed up to ¾ h and then creases fast to the top of short vegetation; the velocity at SM is general large than at BST or BMS (slightly large than BST). In the upper layer (z/h > 1), the averaged velocity varies gradually with depth for BST and SM; however, the velocity at BMS has a different profile: the velocity initially increases slowly to the middle of layer 2 and then rapidly to the water surface, where the flow is not affected by the short vegetation upstream, so the velocity profile of SM is a typical of S-type, as also observed Tang et al. (2021c) and Rahimi et al. (2020).

3.5 Lateral Variation of Depth-averaged Velocity

The depth-averaged and the layer-averaged velocities can be obtained from measured velocity profiles. Figure 7 shows the lateral distribution of layer-averaged and depth-averaged velocity for the half channel. The depth-averaged velocity in Figure 7 reveals that the velocity directly behind the vegetation (at the locations with odd numbers) is generally smaller than those behind the gaps of vegetation (at the locations with even numbers), which are consistent with the results found in the previous sections. In general, the closer to the center, the depth-averaged velocity tends to increase slightly.

Similarly, the layer-averaged velocity directly behind the vegetation is smaller than that behind the gap of vegetation. Note that in layer 3, the layer-averaged velocity at P3, 7 and 11 larger than any other locations, because the flow of layer 3 at those locations (P3, 7, 11) is not affected by the upstream short and median vegetation, whereas the flow of layer 3 at locations P1, 5 and 9 is impacted by the upstream tall vegetation, becoming smaller.

Overall, the averaged velocity of half channel in Figure 8 shows that the velocity is the lowest in layer 1, the highest in layer 3, and the velocity of layer 2 lies between them. The averaged velocity of each layer is related to the density of vegetation: layer 1 has the highest density of vegetation, leading to a smallest velocity, whereas layer 3 has the lowest density of vegetation (only tall vegetation), resulting in a highest velocity.

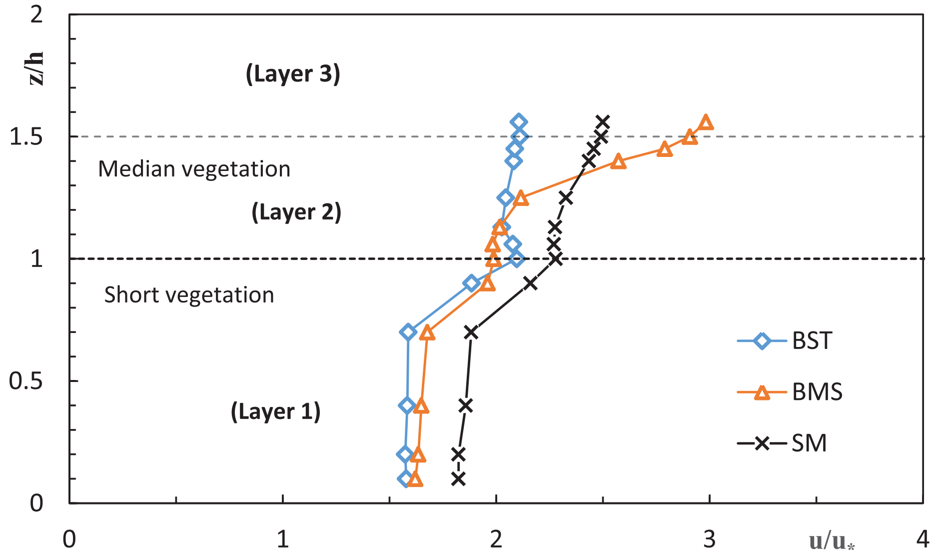

Figure 6. Lateral distribution of depth-averaged velocity.

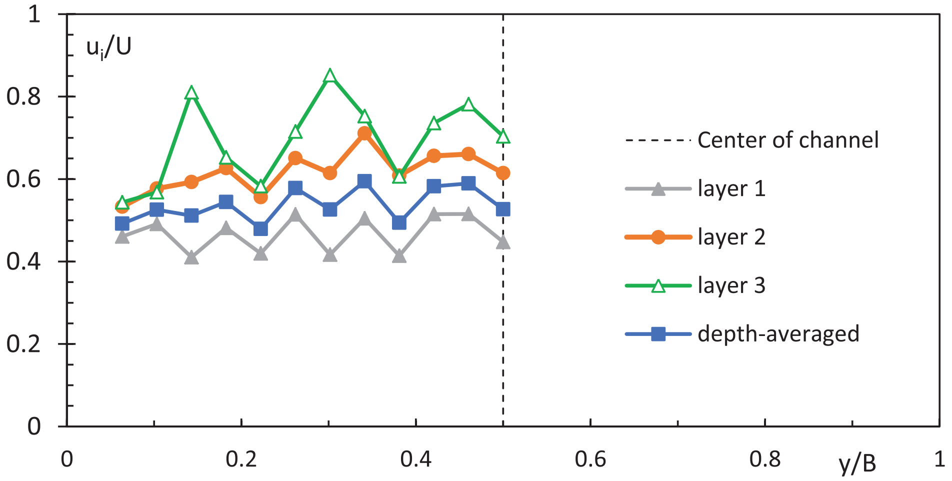

Figure 7. Lateral variation of layer- and depth-averaged velocity.

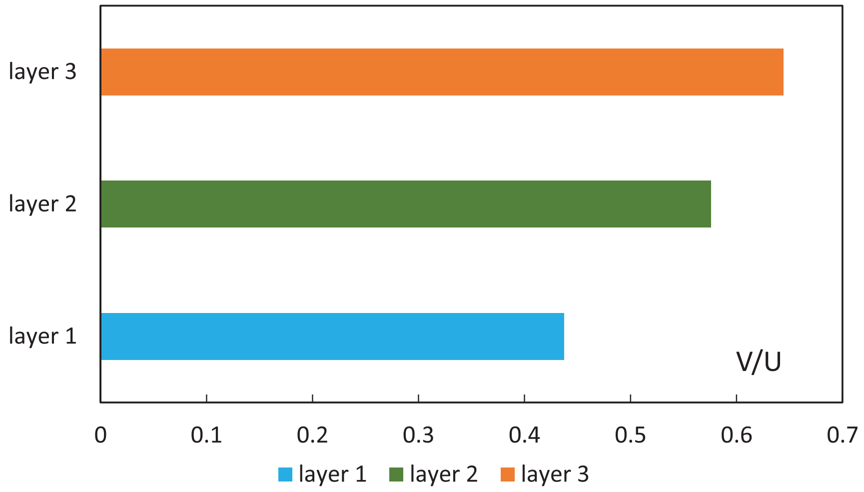

Figure 8. Half channel averaged velocity (V) of each layer, where U is the cross-sectional mean velocity of the whole channel.

3.6 Discussion

In natural rivers and wetlands, various types of vegetation co-exist, showing multiple heights of vegetation. Due to the complexity of the interaction between vegetation and flow, previous research mainly focuses on the flow characteristics of single-layered vegetation through flow under either submerged or emerged conditions. It is unknown how the multi-layered vegetation affects the flow. Our experimental results in this study show the complexity of flow, indicating different velocity profiles depending on the locations behind the vegetation (Figure 5). In general, the velocity profile shows an S-type of profile with two distinct reflections: one at a certain distance (0.25h) below the top of short vegetation, and the other near the top of the short vegetation, which was also observed in the channel flow with two-layered vegetation (Huai et al 2014, Rahimi et al. 2020; Tang et al. 2021a). However, the velocity directly behind median after a short vegetation shows a rapid increase in the upper layer despite the media vegetation being emergent. This velocity profile is like the one observed in the channel with two-layered vegetation fully submerged (Huai et al, 2014; Tang et al. 2021b).

Our experimental results show that the sidewall affects the velocity profiles: the closer to the wall, the smaller the velocity, particularly in the upper layer, as seen in group 1 (P1, 5 and 9) and group 2 (P3, 7 and 11) in Figure 3. This founding also applies to groups 3 (P2, 6, 10) and 4 (P4, 8) in Figure 4. This result is consistent with the theory of boundary layer, which will limit the velocity closer to the solidary boundary, like the sidewall here.

Interestingly, in the flow with vegetation of multiple heights, the velocity profile behind vegetation could be significantly different depending on the combination of upstream vegetation heights. As indicated in Figure 6, the averaged velocity profile directly behind median and short vegetation (at BMS) shows an S-type profile with three reflections, whereas the averaged velocity profile behind short after tall vegetation (at BST) reveals a '□' type profile. The S-type profile agrees with the observed results by Huai et al. 2014 and Tang et al. 2018, which is caused by the combined effect of denser vegetation near bed and the sparse vegetation in the upper layer of flow, like the two-layered vegetation flow. The 'ʃ' type profile is like a velocity profile in a channel with submerged single-layered vegetation, as observed in the literature (Lopez & Garcia, 2001, Tang, 2019a).

It should be noted that the finding in this study is based on the experiment of one particular depth. Certainly, this will be consolidated by more data, for example, at different depths (i.e. submergence ratios) and densities of vegetation in the future.

4. CONCLUSIONS

Velocity measurements have been taken at various locations in a novel experiment of open channel flow, which aims at investigating the effect of vegetation of three heights on the flow. The observed results show that the velocity profiles vary laterally with the positions. In general, the velocity is almost constant in the lower layer ($z/h < 0.5$) and increases rapidly up to the top of short vegetation and then continuously increases to the water surface. The velocity profile has two distinct reflections: one below the top of short vegetation at $z/h = 0.75$, the other near the top of short vegetation. Furthermore, the following points may be drawn:

- The sidewall boundary has a certain impact on velocity profiles: the closer to the wall, the smaller the velocity, particularly in the upper layer (z/h>1).
- The velocity profiles behind the gap of vegetation are generally larger than those directly behind the vegetation.
- The velocity profiles directly behind vegetation are affected by the pattern of vegetation upstream: in the upper layer (z/h>1), the velocity increase slowly with the depth when upstream tall vegetation exists, but it creases rapidly to the water surface when upstream short vegetation occurs.
- The layer-averaged velocity directly behind the vegetation is smaller than that behind the gap of vegetation. In general, the closer to the center, the depth-averaged velocity tends to increase slightly.
- The averaged velocity of each layer is related to the density of vegetation: layer 1 has the highest density of vegetation, leading to the smallest velocity, whereas layer 3 has the lowest density of vegetation (only tall vegetation), resulting in the highest velocity.

5. ACKNOWLEDGEMENTS

The authors acknowledge the support by XJTLU via the fund (REF-20-02-03, PGRS2012007, RDF-16-02-02, SURF2021012).

6. REFERENCES

Anjum, N., and Tanaka, N. (2019). Hydrodynamics of longitudinally discontinuous, vertically double layered and partially covered rigid vegetation patches in open channel flow. *River Research and Application*, 2019: 1-13.

Anjum, N., Ghani, U., Pasha, G. A., Latif, A., Sultan, T., and Ali, S. (2018). To investigate the flow structure of discontinuous vegetation patches of two vertically different layers in an open channel. *Water,* 10(1), 75.

Carollo, F.G., Ferro, V., and Termini, D. (2002). Flow velocity measurements in vegetated channels. *Journal of Hydraulic Engineering*, 128(7), 664-673.

Caroppi, G., Gualtieri, P., Fontana, N. and Giugni, M. (2020). Effects of vegetation density on shear layer in partly vegetated channel. *Journal of Hydro-Environment Research*, 30 (2020), 82-90.

Chembolu, V., Kakati, R., and Subashisa Dutta, S. (2019). A laboratory study of flow characteristics in natural heterogeneous vegetation patches under submerged conditions. Advances in Water Resources, 133 (2019): 103418.

Chen, G., Huai, W., Han, J. and Zhao, M. (2010). Flow structure in partially vegetated rectangular channels. *Journal of Hydrodynamics*, 22(4), 590-597.

Curran, J., Hession, W. (2013). Vegetative impacts on hydraulics and sediment processes across the fluvial system. *Journal of Hydrology*. 505, 364–376.

Ghisalberti, M..and Nepf, H.M. (2002). Mixing layers and coherent structures in vegetated aquatic flows. *J. Geophys Research*, 107(C2):11.

Ghisalberti, M. and Nepf, H. (2006). The structure of the shear layer in flows over rigid and flexible canopies. *Environmental Fluid Mechanics*, 6(3), 277-301.

Huai, W., Wang, W., Hu, Y., Zeng, Y. and Yang, Z. (2014). Analytical model of the mean velocity distribution in an open channel with double-layered rigid vegetation. *Advances in water resources*, 69, 106-113.

Liu, D., Diplas, P. Fairbanks, J.D. and Hodges, C.C. (2008). An experimental study of flow through rigid vegetation. *Journal of Geophysical Research: Earth Surface*, 113.

Lopez, F., and Garcia, M.H. (1998).Open-channel flow through simulated vegetation: suspended sediment transport modeling. *Water Resource Research,* 34(9):2341–2352.

Lopez, F., and Garcia, M.H. (2001). Mean flow and turbulence structure of open-channel flow through non-emergent vegetation. *Journal of Hydraulic Engineering*, 127(5), 392–402.

Naiman, R.J. Decamps, H., and Pollock, M. (1993). The role of riparian corridors in maintaining regional biodiversity. *Ecological Application*, 3: 209-212

Neary, V. S. (2003). Numerical solution of fully developed flow with vegetative resistance. *Journal of Engineering Mechanics*, 129(5), 558-563.

Nepf, H. M. (2012). Hydrodynamics of vegetated channels. *Journal of Hydraulic Research*, 50(3): 262-279.

Nezu, I., and Sanjou, M. (2008). Turbulence structure and coherent motion in vegetated canopy open-channel flows. *Journal of Hydro-Environment Research*, 2(2), 62-90.

Nikora, N., Nikora, V. and O'Donoghue, T. (2013). Velocity profiles in vegetated open-channel flows: combined effects of multiple mechanisms. *Journal of Hydraulic Engineering*, 139(10), 1021-1032.

Okamoto, T., and Nezu, I. (2013). Spatial evolution of coherent motions in finite - length vegetation patch flow. *Environmental Fluid Mechanics*, 13: 417-434.

Rahimi, H., Tang, X., Singh, P., Li, M., and Alaghmand, S. (2020). Analytical model for the vertical velocity profiles in open channel flows with two layered vegetation. *Advances in Water Resources*, 137(3), 103527, DOI: 10.1016/j.advwatres.2020.103527.

Rahimi, H.R., Tang, X., and Singh, P. (2019). Experimental and numerical study on impact of double layer vegetation in open channel flows. *Journal of Hydrologic Engineering*, 25(2), 04019064, DOI:10.1061(ASCE)HE.1943-5584.0001865

Singh, P., Rahimi, H. and Tang, X. (2019). Parameterization of the modeling variables in velocity analytical solutions of open-channel flows with double-layered vegetation. *Environmental Fluid Mechanics*, 19(3), 765-784.

Souliotis, D. and Prinos, P. (2011). Effect of a vegetation patch on turbulent channel flow. *Journal of Hydraulic Research*, 49(2), 157-167.

Stone, B. M. and Shen, H. T. (2002). Hydraulic resistance of flow in channels with cylindrical roughness. *Journal of Hydraulic Engineering*, 128(5), 500-506.

Tang, X. and Ali, S. (2013). Evaluation of methods for predicting velocity profiles in open channel flows with submerged rigid vegetation. In *Proceedings of the 35th IAHR World Congress*, Vol.4, B1, 1-12, Sept. 8-13, 2013, Chengdu, China. ISBN: 978-7-89414-588-8.

Tang, X. (2019a). A mixing-length-scale-based analytical model for predicting velocity profiles of open channel flows with submerged rigid vegetation. *Water and Environment Journal*, 33(4), 610-619.

Tang, X. (2019b). Evaluating two-layer models for velocity profiles in open-channels with submerged vegetation. *Journal of Geoscience and Environment Protection*, 7(1), 68-80.

Tang, X., Guan, Y., Rahimi, H., Singh, P. and Zhang, Y. (2021a). Discharge and velocity variation of flows in open channels partially covered with different layered vegetation. *International Conference on Environmental Engineering, Agricultural Pollution and Hydraulical Studies* (EEAPHS 2021), May 29-30, 2021, Wuhan, China. E3S Web of Conferences 269, 03001 (2021), DOI: 10.1051/e3sconf/202126903001.

Tang, X. and Hu, Y. (2021). Impact of partially covered vegetation on the lateral velocity distribution of open channel flow. *Journal of Geoscience and Environment Protection*, 9 (4), 1-10

Tang, X., Lin, P., Liu, P. LF. and Zhang, X. (2021b). Numerical and experimental studies of turbulence in vegetated open-channel flows. Environmental Fluid Mechanics, 21: 1137-1163 (2021)

Tang, X., Rahimi, H., Singh, P., Wei, Z., Wang, Y., Zhao, Y. and Lu, Q. (2018). Experimental study of open-channel flow with partial double-layered vegetation. *Proceedings of the 1st International Symposium on Water Resource and Environmental Managemen*t (WREM 2018), 1-7, Nov. 28-29, 2018, Kunming, China. DOI: 10.1051/e3sconf/20198101010.

Tang, X., Rahimi, H.R., Guan, Y. and Wang, Y. (2021c). Hydraulic characteristics of open-channel flow with partially-placed double layer vegetation. *Environmental Fluid Mechanics*, 21 (2): 317–342

Yang, F., Huai, W-X., and Zheng, Y-H. (2020). New dynamic two-layer model for predicting depth-averaged velocity in open channel flows with rigid submerged canopies of different densities. *Advances in Water Resources,* 138(2020), 103553.