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Effect of Mixed Vegetation of Different Heights on Open Channel Flows

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Abstract

Vegetation of different heights commonly grows in natural rivers, canals and wetlands and affects the biodiversity and morphological process. The role of vegetation has drawn great attention in river ecosystems and environmental management. Due to the complexity of the vegetated flow, most previous research focuses on the effect of uniformed one-layered vegetation on the flow structure and morphological process. However, less attention was paid to the impact of the mixing vegetation of different heights, which is more realistic and often occurs in natural riverine environments. This paper aims to investigate the effect of mixing three-layered vegetation on flow characteristics, particularly the velocity distribution, via a novel experiment. Experiments were performed in a titling water flume fully covered with vegetation of three heights (10, 15 and 20 cm) arranged in a staggered pattern, which is partially submerged. Velocities at different positions along a half cross-section were measured using a mini propeller velocimeter. Observed results showed that the velocity has a distinct profile directly behind vegetation and behind the vegetation gap. The overall profile has two distinct reflections about ¼ below or near the top of short vegetation (h): the velocity remains almost constant in the bottom layer (<0.75 h) and then fast increases until the top of short vegetation; after a gradual increase, the velocity rapidly increases to the water surface. Moreover, in the upper layer ($z > h$) the velocities directly behind the middle after short vegetation increase much faster than those directly behind the short after tall vegetation. The finding in this study would help river riparian and ecosystem management.

Keywords

Rigid Vegetation, Mixed-Layered Vegetation, Riparian, Velocity Distribution, Submerged Flow, Open Channel

1. Introduction

In recent years, aquatic vegetation has drawn great attention from research because it plays an important role in rivers, wetlands, and coastal systems, influencing nutrient transmission, morphological and biogeochemical processes (Wang et al., 2015; Nepf, 2012). The presence of vegetation in the watercourse alters the flow structure (Tang et al., 2023a; Caroppi et al., 2020; Nezu & Sanjou, 2008; Ghisalberti & Nepf, 2002), reduces flow velocity (Zhang et al., 2022; Stone & Shen, 2002; Lopez & Garcia, 2001), and consequently affects the discharge (Tang et al., 2021a). Vegetation is also known to provide ecosystem functions, for example, erosion control (Curran & Hession, 2013; Rominger et al., 2010), an increase in habitat diversity (Naiman et al., 1993), and water quality improvement (Cotton et al., 2006). Therefore, understanding the flow through vegetation helps to manage the river ecosystem better.

Due to the complexity between vegetation and flow interaction, previous research mainly focuses on the flow through single-layered vegetation in laboratory flumes, such as the velocity and flow resistance of rigid vegetation and under either emergent or submerged flow conditions (e.g. Wang et al., 2022; Tang, 2019a; Stone & Shen, 2002), the velocity profile prediction (Tang, 2019a, 2019b, 2019c; Singh et al., 2019; Nikora et al., 2013), and turbulence characteristics (Tang et al., 2023a; Kumar and Sharma, 2022). Meanwhiles, due to the limitation in space, measurement and time of experiments, numerical methods have been developed to study the flow structure in vegetated flow by numerical simulation (e.g. Souliotis & Prinos, 2011; Dehrashid et al., 2023) or CFD (e.g. Anjum & Ali, 2022; Rahimi et al., 2019).

Vegetation of various types (e.g. grasses, shrubs and trees) is often mixed in natural aquatic environments. Usually, tall vegetation is emergent, but shorter vegetation is submerged in high flood flows. Limited experimental studies have been performed on the flow through a mixing array of short and tall vegetation, so-called double or two-layered vegetation (e.g. Tang et al., 2021b; Rahimi et al., 2020; Tang et al., 2019; Huai et al., 2014), showing significant different velocity profiles from the flow through one-layered vegetation. It is still poorly understood how multi-layered vegetation affects the flow.

To further study the effect of the mixed vegetation of different heights on the flow, this paper presents a novel experimental study to investigate the lateral and vertical change of flow velocity in the channel with three-layered vegetation under the flow condition: short and median height vegetation was submerged while the tall vegetation was emergent.

2. Experimental Description

The experiments were undertaken in the titling water flume of 20 m × 0.4 m × 0.5 m at a fixed channel slope of 0.003 at Xi'an Jiaotong-Liverpool University (XJTLU). The side view of the flume is shown in **Figure 1** (Tang & Hu, 2021), where a 4.3 m long vegetation section starts 8.4 m from the flume inlet. Plastic

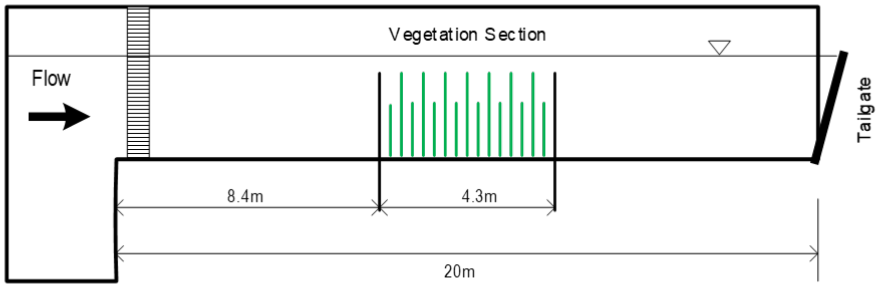

Figure 1. The schematized channel in the study.

rods of 6.35 mm in diameter were used to simulate the rigid vegetation in heights 0.1, 0.15 and 0.2 m, representing the short, middle and tall vegetation, respectively. All rods are arranged in a staggered pattern with a spacing interval of 31.75 mm between adjoining rods, as shown in **Figure 2**. The distance of rod near each wall is 25.38 mm.

In the test, 12 typical locations along a half channel were measured velocity using a mini propeller velocimetry, denoted by symbol x in **Figure 2**. A flow depth of 17 cm in the test section was achieved for a flow rate of 17.55 L/s, which means that only tall rods were not submerged. At each position, 16 points of velocity were vertically measured using the velocimetry in a sample of 20 s to minimize the error.

3. Results

For a better comparison of the results, the velocity in all subsequent figures is nondimensionalized by the channel mean velocity (U), while the vertical distance (z) above the channel bed is normalized by the short vegetation height (h). Moreover, the measured locations are as follows: P1, P5 and P9 (P denotes the position) are directly behind the short after tall vegetation; P3, P7 and P11 are directly behind the middle after short vegetation, whereas the points with even numbers (P2, 4, 6, 6, 8, 10, 12) represents the locations behind the gap between short and middle vegetation. Note that P12 is at the central line of the channel and the vegetation is not symmetrically distributed along the central line.

3.1. Lateral Variation of Velocity Profiles Directly Behind Vegetation

To understand whether the vegetation impacts the velocity distribution, **Figure 3** shows velocities at four specific locations directly behind vegetation (i.e. at P1, 3, 9 and 11). Note that P1 and P9 are at the same position as Group A1, i.e. directly behind the short after tall vegetation, whereas P3 and P11 are at the same position as Group A2, which are directly behind the middle after short vegetation. Overall, all the velocity profiles in Group A have small vertical variations (almost constant) near the bed up to a distance below the top of short vegetation (approximately $z/h < 0.75$), and then fast increases until the top of short vegetation, where the velocity has a reflection. Afterwards, in the area above the short

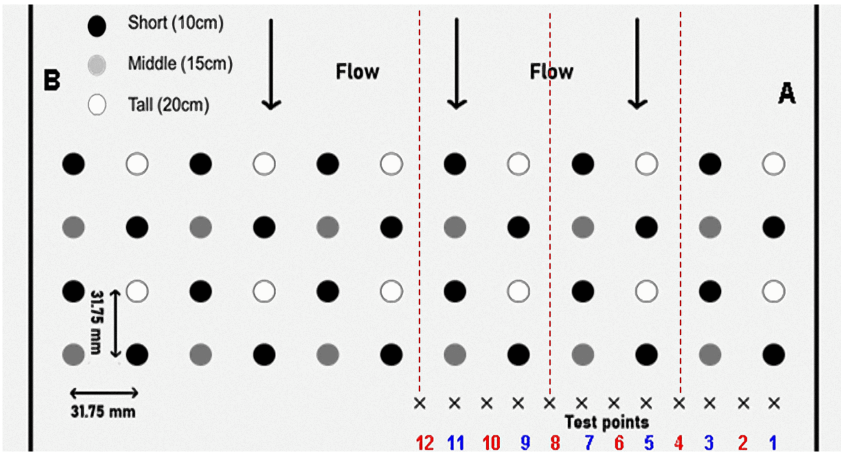

Figure 2. The location plan of vegetation and measurement in the test.

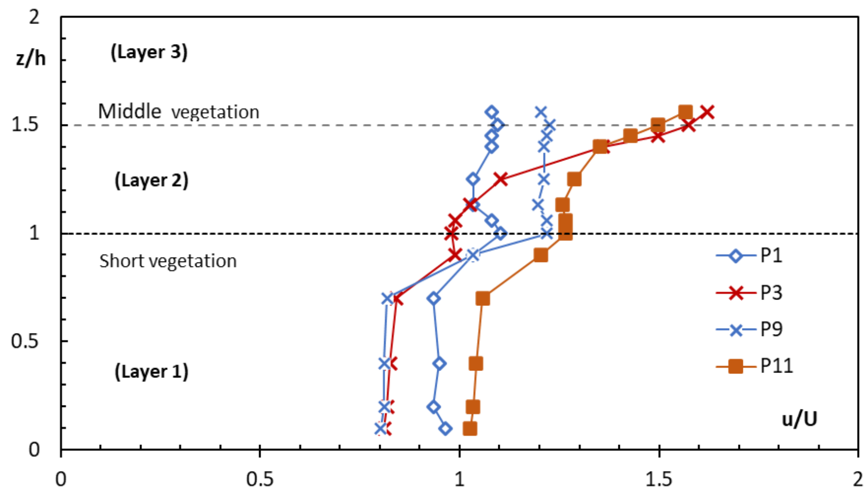

Figure 3. Comparison of velocity profiles directly behind vegetation.

vegetation, two groups have different profiles: the velocity in Group A1 has little variation from z = h to the water surface, but the velocity in Group A2 initially has a small increase near the top of short vegetation and then rapidly increases to the water surface. The distinct velocity profiles above z = h demonstrate the impact of the upstream vegetation. As Group A1 are behind the short after tall vegetation, which is like double-layered vegetation, the velocity profile in Group A1 reveals a typical velocity vertical distribution of double-layered vegetation flow, given by Rahimi et al. (2020). The small variation of velocity in layers 2 and 3 of Group A1 is affected by the upstream tall vegetation due to its retarding and bocking effect. However, the large vertical variation in velocity above z = h of Group A2 is due to less impact from upstream short vegetation, thus producing a similar profile of fully submerged vegetation, as shown by Tang et al. (2023b).

A close examination of the velocity profiles in **Figure 3** shows the different effects of vegetation and wall. In the layer above the short vegetation (z > h), the closer to the wall, the smaller the velocity in the zone; see P9 > P1 and P11 > P3. In the bottom layer close to the bed (i.e. z < h), the same applies to Group A2;

however, it does not apply to Group A1, where the velocity near the wall (P1) is larger than that (P9) near the channel center. This result implies that the velocity very close to the wall (P1) is relatively less affected by the vegetation.

3.2. Lateral Variation of Velocity Profiles behind Vegetation Gap

To identify lateral changes of velocity profiles behind vegetation gap, the velocity profiles of P2, 4, 8 and 10 are given in **Figure 4**. In terms of the relative position of upstream vegetation, P2 and P10 are at the same position (Group B1), i.e. behind the gaps of upstream short and middle vegetation in the way away from wall A, whereas P4 and P12 are at the same position (Group B2), i.e. behind the gap of upstream the middle and short vegetation. Generally, the velocities near the bottom are almost the same for all positions, and similarly to Group A, there are small variations in the lower layer up to z/h = 0.75. However, the velocity differs in the upper layer (z/h > 0.8), depending on the relative position to the wall. Overall, the closer to the wall, the smaller the velocity for each group. Moreover, in the upper layer, the velocity at the position near wall (P2 and P4) have much less variation with depth, compared to those at the positions far away the wall (P8 and P10), implying that the additional blocking effect of wall to the velocity.

3.3. Comparison of Velocity behind Vegetation and Behind Gaps

As shown in the previous sections, the positions influence the velocity profile. The main difference is in the upper layer (z/h > 1), where vegetation is under different submergence conditions. **Figure 5** shows the averaged profiles for three typical locations to obtain the overall velocity profiles at some typical locations. BST represents the averaged profiles at P1, 5, 9 (directly behind the short after tall vegetation), BMS denotes the average at P3, 7, 11 (directly behind the middle after short vegetation), and SM is the averaged velocity at P2, 4, 6, 8, 10 (behind the short and middle vegetation gap).

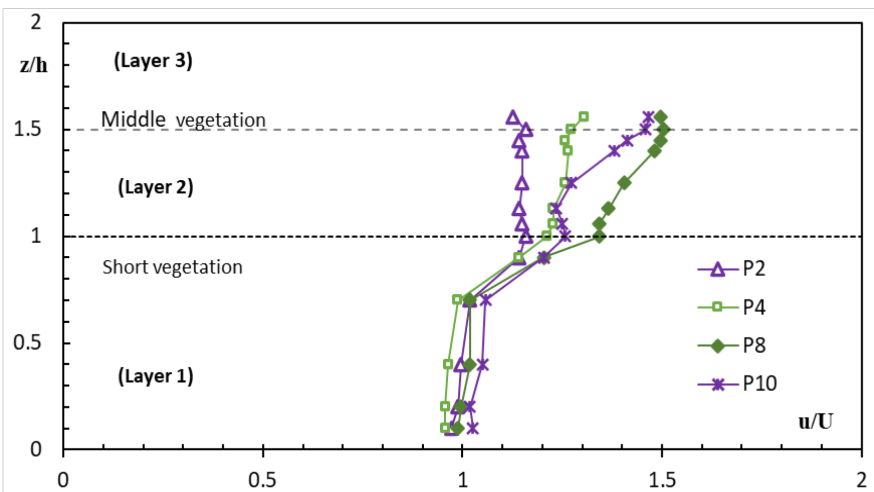

Figure 4. Lateral change of velocity profiles behind the vegetation gap.

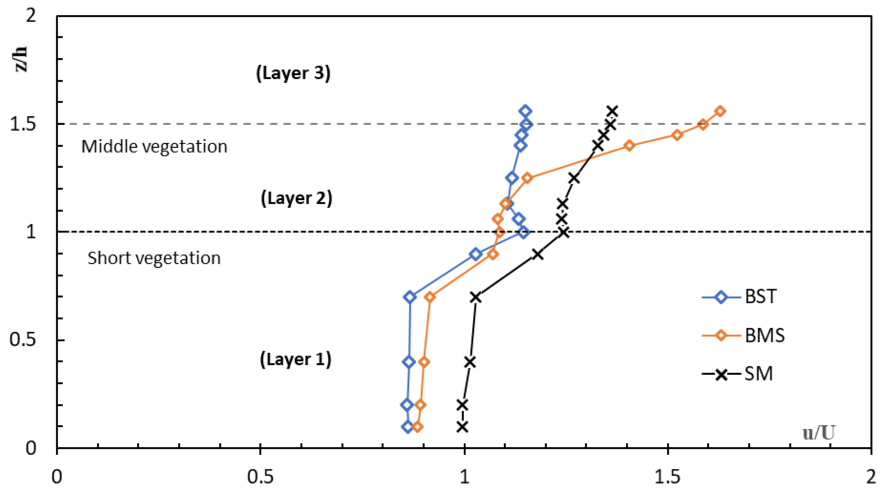

Figure 5. Comparison of velocity profiles behind vegetation and the vegetation gap.

The three typical locations (BST, BMS and SM) have distinct velocity profiles: In the bottom layer (layer 1, z/h < 1), the averaged velocity shows a similar profile, i.e. the velocity varies small near the bed up to z = 0.75 h and then increases fast to the top of short vegetation, where a velocity reflection occurs; the velocity at SM is larger than at BST or BMS (slightly larger than BST). In the upper layer (z/h > 1), The velocity increases gradually with depth for BST and SM (larger than BST), but the velocity at BMS increases rapidly in a different profile: the velocity increases slowly to about z/h = 1.25 and then rapidly to the water surface, where the flow is not affected by the short vegetation upstream, resulting in a type of S-shape velocity, which is also observed Tang et al. (2021b) and Rahimi et al. (2020).

3.4. Lateral Change of Zonal Velocity and Zonal Discharge

For engineering applications, understanding the averaged velocity in different zones along a cross-section would help evaluate the discharge distribution and flow resistance. This section explores how the zonal velocity and discharge change along the channel, which is analyzed by splitting the half channel into three zones, named B1-4, B4-8 and B8-12, as shown in **Figure 6**. Zone B1-4 is the region from wall A to location P4. Zone B4-8 denotes the region from P4 to P8, while Zone B8-12 denotes the region from P8 to P12. Each zone is approximately one-sixth of the channel width. BL means the half channel.

The weighted average velocity for all zones has a similar profile: The velocity remains almost constant in the bottom layer (z/h < 0.75), increases fast to the top of short vegetation (z/h = 1), and then increases gradually to the middle of layer 2 (1 < z/h < 1.5); afterwards, it increases fast until the water surface in the upper layer (z/h > 1.5). The overall velocity is a type of "S" profile. Moreover, the closer to the wall, the larger the overall velocity (i.e. B8-B12 > B4-8 > B1-4).

Based on the weighted average velocity for all zones, the correspond zonal discharge through each zone can be computed, as shown in **Figure 7**, which

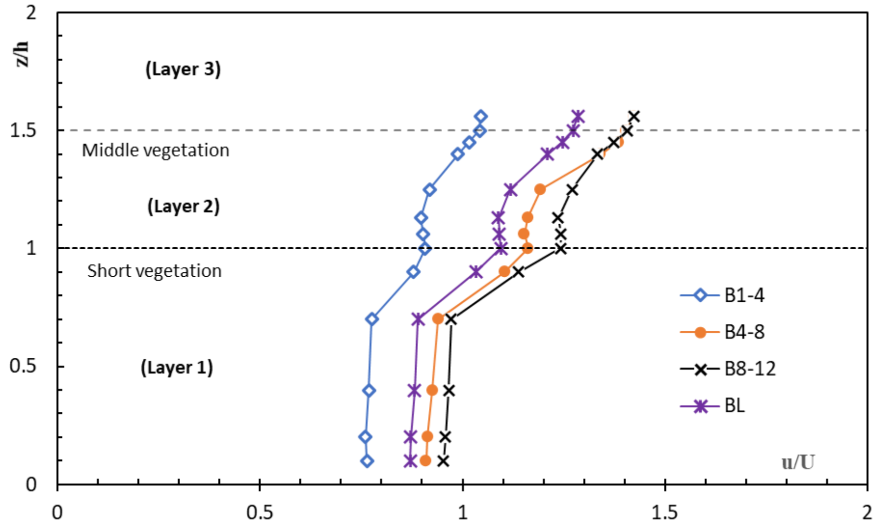

Figure 6. Comparison of zonal averaged velocity profiles.

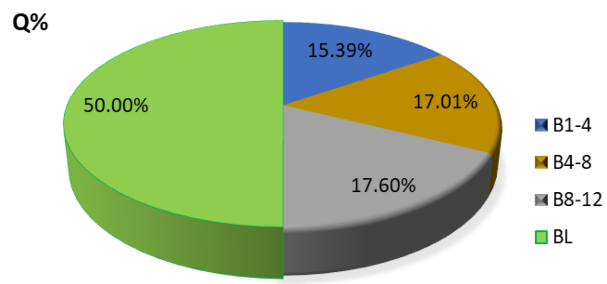

Figure 7. Percentage of zonal discharge in the vegetation.

shows that discharge in the zone closer to the wall (B1-4) is about 2% smaller than that in B4-8 or B8-12 (almost the same as B4-8). This result is consistent with the velocity profile in **Figure 6**.

4. Discussion

The presence of vegetation will lead to the interaction between vegetation and flow laterally and vertically in the submerged state. The complexity will be increased when the vegetation of different heights co-exists. Our experimental results in this paper have demonstrated the complexity of the flow field: Different velocity profiles occur depending on the position behind the vegetation (**Figure 5**). Overall, the velocity is a type of profile with three distinct reflections: at a certain distance (0.25 h) below and close to the top of short vegetation, and the third near the top of the middle vegetation, which was also observed in the flow through two-layered vegetation (Tang et al., 2021b; Huai et al., 2014). However, the velocity directly behind the middle after short vegetation shows a rapid increase in the upper layer (z/h > 1.25) because of the middle vegetation in the fully submerged status. The velocity profile of BMS is similar to the one observed in the channel with two-layered vegetation fully submerged (Tang et al., 2023b; Huai et al., 2014).

Our results also show the effect of the sidewall on the velocity profiles: the closer to the wall, the smaller the velocity, particularly in the upper layer (z/h > 1), as seen in Group A (P1 vs P9; P3 vs P11) in **Figure 3** and Group B in **Figure 4**. This result is confirmed by the weighted average velocity in **Figure 6**, showing the additional retarding effect of the wall.

It is worth noting that the finding of distinct velocity profiles is based on one test depth (see BST and BMS in **Figure 6**). More tests of other depths are encouraged to establish this result.

5. Conclusion

A novel experiment was undertaken on a water flume covered with mixed vegetation of three heights to study the impact of vegetation on flow velocity. The measured results show that the velocity profiles differ with the positions. Overall, 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 shows two distinct reflections: one near z/h = 0.75, the other near the top of short vegetation. In addition, the following points can be drawn.

- The effect of sidewall on the velocity: the closer to the wall, the smaller the velocity, particularly in the upper layer (z/h > 1).
- The velocity profiles directly behind vegetation are affected by the pattern of upstream vegetation: 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 velocity directly behind the vegetation is generally smaller than that behind the vegetation gap because of the blockage effect of vegetation.
- The velocity at different heights is related to vegetation density: small velocity in the lower layer and high velocity in the upper layer result from the corresponding lower and high vegetation density.

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Conflicts of Interest

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

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