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THREE-DIMENSIONAL FLOW CHARACTERISTICS IN A CHANNEL WITH EMERGENT RIGID VEGETATION

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Abstract

Various flow characteristics such as velocity distributions, turbulence characteristics, mass and momentum exchange between the vegetated and non-vegetated regions. Aquatic plants are responsible for reducing sediment transport, erosion control and turbidity, water quality, nutrient and particulate removal significantly. The studying and understanding of the vegetation effect on the natural flow is an important objective in modern scientific research about flow structure, flood control, river restoration and management with high environmental impact. Therefore, in the present study, the effect of emergent rigid vegetation with staggered configuration in an open channel is studied through a straight rectangular flume experiment. Three-dimensional vertical distribution of velocity, turbulence intensity, and Reynolds shear stress for vegetated and non-vegetated area is analyzed and compared between them. The results show that the streamwise, lateral and vertical velocity are found to be smaller, higher with negative magnitude and smaller, respectively within the vegetated area than the non-vegetated area. Near the bed surface, a strong upward velocity present in the vegetation area and decreasing towards upper surface. Streamwise and lateral turbulence intensities are stronger for vegetation area. Three-dimensional Reynolds shear stress and turbulent kinetic energy are also evaluated in this study. This experiment provides a vital interpretation to understand flow characteristics in non-vegetation and vegetation area.

Keywords: *Turbulent, Velocity, Reynolds Shear Stress, Rigid vegetation*

1. Introduction

The fluid properties are extremely complicated where flow passes via riparian aquatic plants. Vegetation tends to affect sedimentary mechanisms and is essential in current river management and hydraulics of rivers. Even, since the flow capacity in the river can be investigated by removing the vegetation in full or in part, such investigations can help to identify the hike in the loads of sediments borne by the flowing water. The impact of vegetation on flow depends on the channel characteristics as well as vegetation characteristics. The vegetation along the stream bed plays a big role in the hydrodynamic behaviour, in the ecological balance and on the features of the river (Chembolu et al., 2017). Aquatic vegetation in conveyance channels improves the flow resistance thereby decreasing transportation potential and has historically been regarded a hazard and has therefore been eliminated from channels to improve the rate of flow (Wu et al, 2020). In literatures, various authors executed field and laboratory experiments related to vegetation (Sukhodolov et al., 2017). Experiments in laboratory observing flow behaviour, determining distribution of velocity in presence of vegetation and resistance offered by different types of vegetation (Rahimi et al., 2020; Devi et al., 2017); and numerical investigation were conducted to understand flow interactions in vegetated channel (Li et al., 2022; Dehrashid et al., 2022).

In previous investigation, many researchers focused on the study of drag coefficient, Manning roughness coefficient, velocity distributions and turbulent flow characteristics. The study of the vegetation effect on the natural flow is an important objective in modern scientific research about flow structure, flood control, river restoration and management with high environmental impact. The study will be helpful for finding the three-dimensional velocity components and turbulence characteristics in a straight rectangular concrete bed channel with emergent rigid vegetation in staggered configuration and compared with non-vegetated region. The effect of emergent rigid vegetation on three-dimensional velocity, turbulence intensity and Reynolds shear stress for vegetated and non-vegetated region have been studied. The turbulent kinetic energy is also analyzed to understand the interaction between vegetation and non-vegetation region.

2. Methodology

The experiments were performed in a concrete bed simple rectangular channel whose dimensions are 13 m long, 0.9 m wide and 0.7 m deep shown in Fig.1. The bed slope of channel was 0.0015. A tank was provided upstream of the channel to adjust uniform flow into the channel. In this study three pumps are used for extract water from storage tank that store water in an inlet tank. In the main channel water comes from the inlet tank which is released by overhead tank. A vertical gate is connected in upstream portion and joining the turbulence dissipater to reduce the turbulence and approach velocity. In downstream portion, the flow depth is maintained by an adjustable tail gate which is also ensure uniform flow. The vegetation was started from a distance of 3 m from head gate and ending before 3 m from tail gate. The vegetation area was 7m. The diameter and height of the vegetation stem are 8 mm and 25cm, respectively. The vegetation stem was placed in staggered pattern and the spacing between vegetation stem was 18 cm (Fig. 1).

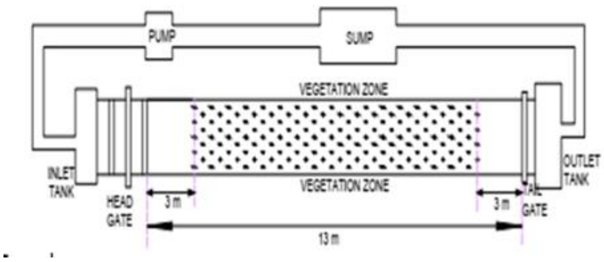

Fig. 1 Plan view of channel

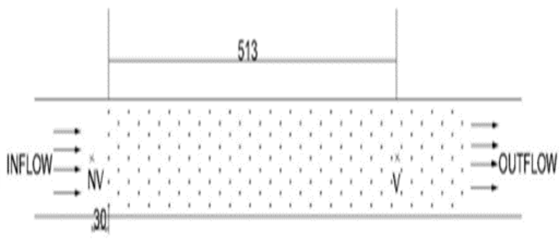

Fig. 2 Plan view of test section

In this experimentation, a three-dimensional 5 cm down-looking Micro Acoustics Doppler Velocimeter (ADV) instrument was used for instantaneous velocity measurement. A sample size of 9000 at a frequency of 50 Hz with 180 seconds sampling time at each location. The ADV data was filtered by WinADV software with a correlation of 70% and signal- to-noise-ratio level of 15 dB (Devi et al., 2017). The velocity data was not taken for a depth less than 5 cm from the top surface of water, due to configurations of the ADV. A point gauge was used for determined flow depth in channel. All the experimental conditions are described in table 1. The sampling data was taken at two sections (NV, V) shown in (Fig. 2). Test section was located at 30 cm before vegetation started, and 513 cm after vegetation started in the centre of channel cross-section for non-vegetated and vegetated region, respectively. The selections of test section were such a way in the channel should be minimized the effects of flow entrance and exit conditions and at measurement section flow is fully developed.

Table 1. Description of experimental condition

Flow discharge (m^3/s)	Reynolds number	Flow depth (cm)	Vegetation type	Vegetation distribution	Vegetation spacing (cm)	Solid volume fraction
0.06148	50194	20	Emergent rigid	Staggered	18	0.15514

3. Results and Discussion

3.1 Velocity profile

The time-averaged velocity components are represented by u, v, and w, where u, v and w are average velocities in the streamwise, lateral and vertical directions respectively. All velocity components are normalized by discharge velocity (U), which was uniform throughout the flume. All normalized velocities are drawn against normalized depth of flow, where height from bed was made normalized by the depth of flow (y/H, where y = height from bed and H = total flow depth) shown in (Fig 3). In (Fig. 3a), the result shows that the streamwise velocity profiles in the vegetated region are smaller as compared to the non-vegetated region. Near the bed surface streamwise velocity is also decreases in the vegetation region. It means when flow enters from non-vegetated region to vegetated region then velocity decreases due to resistance offered by vegetation stem. In vegetated region, magnitude of normalized streamwise velocity lies between (0.65-0.7) except near the bed surface. Streamwise velocity decreases approximately (30-35) % in vegetated region than that at non-vegetated region. The decrease in velocity near the bed surface in vegetation region is observed. It is significantly reducing when the flow reached in vegetated region. The vertical distribution of streamwise velocity achieved maximum velocity towards free surface and it decreases towards bed because of the drag was imposed by the vegetation. Similar results were observed by other researchers (Liu et al. 2008, Devi et al. 2017). The extra surface area of the vegetation considerably boosts the plants' capacity to absorb momentum, indicating that time-averaged velocities are reducing within the vegetation region. It revealed that emergent rigid vegetation decreased the flow velocity in the channel due to the occurrence of secondary flow and frictional resistance exerted by the vegetation. Fig. 3b shows that the lateral velocity profile in vegetation and non-vegetation region transverse velocity does not follow any regular path as streamwise velocity.

It shows strong negative bulges in inner layer of flow depth. Intensity of lateral velocity is smaller for non-vegetated region as compared to vegetated region. It means intensity of lateral velocity increases in negative direction when flow enters from non-vegetated region to vegetated region. The wake area dominates in the vegetation region due to the vegetation stem. Towards the free surface, it moves gradually in positive direction. The positive lateral velocity represents the flow diversion away from vegetation and negative velocity represents that a flux towards centre of wake (Sharil et. al., 2016).

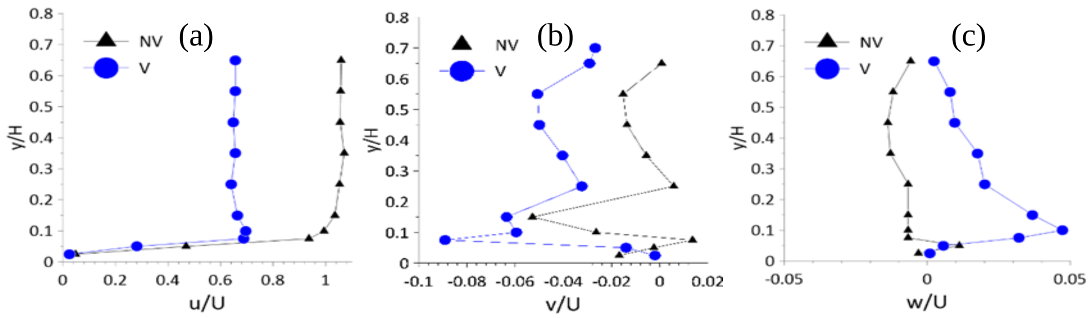

Fig. 4 Normalized velocity profile along (a) streamwise, (b) lateral, and (c) vertical direction

Fig. 3c shows that the vertical velocities in vegetated region and non-vegetated region. In the vegetation region, vertical velocities are moving in upward direction and magnitude is reduces in the direction of free surface; but vertical velocity are moving in downward direction throughout the flow depth at non-vegetated region. In vegetated region, vertical velocity is smaller at outer layer of flow depth as compared to inner layer. Near the vicinity of bed surface, it is close to zero for vegetated and non-vegetated region after that it shows a positive bulge at inner layer of both sections. In this observation, it is noticed that vertical velocity in non-vegetated region and vegetated region are opposite in direction. The additional bed roughness results in a sharper inflection point which likely triggers more vigorous instability and associated coherent structure, evidenced by the vorticity augmentation near the bed due to flow separation (Liu et al., 2008). On the basis of continuity and momentum balance, the higher momentum fluid moving towards the vegetation region from the non-vegetation region displaces the slower fluid behind the vegetation stem.

3.2 Turbulent intensity

The vertical profile of normalized streamwise turbulent intensity u^+ [$u^+=u_{rms}/U= (\overline{u'^2})^{0.5}/U$, where u' is fluctuation of u], normalized lateral turbulent intensity v^+ [$v^+=v_{rms}/U= (\overline{v'^2})^{0.5}/U$,, where v′ is fluctuation of v] and normalized vertical turbulent w^+ [$w^+=w_{rms}/U= (\overline{w'^2})^{0.5}/U$], where u', v′ and w' are fluctuations of u, v and w are drawn against normalized depth of flow (Figs 4). Fig. 4a shows that streamwise turbulent intensity in vegetated and non-vegetated region. u+ is higher in vegetated region as compared to non-vegetated region. In vegetated region and non-vegetated region, magnitude u+ is approximately lies between (0.13-0.14) and (0.11-0.12) respectively except near the bed surface. u+ is increased by approximately 20% in the vegetated region as compared to non-vegetated region. Near the bed surface, it is also higher for vegetated region. The results are quite matched with Liu et al. (2008). When flow passes from non-vegetated region to vegetated region in the channel then streamwise turbulent intensity increases. Fig. 4b shows that the lateral turbulent intensity (v^+) in vegetated and non-vegetated region. It is also higher in vegetated region as compared to non-vegetated region. v^+ is increased by (20-30) % in the vegetated region. When flow enters from non-vegetated region to vegetated region then lateral turbulent intensities increases in the channel for the case of emergent rigid vegetation.

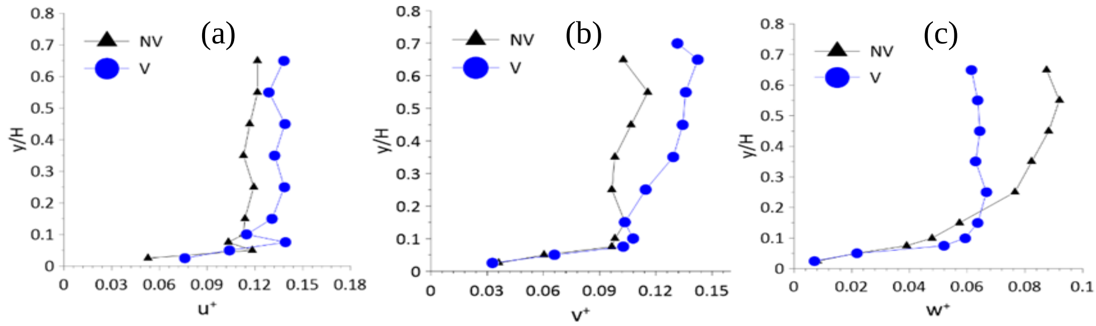

Fig. 4 Normalized turbulent intensity along (a) streamwise, (b) lateral, and (c) vertical direction

In Fig. 4c, the result shows that the vertical turbulent intensity is higher in inner layer of flow depth (y/H < 0.2) and smaller in outer layer of flow depth (y/H > 0.2) at vegetated region as compared to non-vegetated region. At vegetated region, vertical turbulent intensity looks like a vertical straight line in outer layer of flow depth, whose normalized magnitude is approximately (0.52-0.65) except near the bed surface; but at non-vegetated region, it increases gradually towards free surface throughout the flow depth. In non-vegetated region, it is gradually increases towards free surface from bed surface. In inner layer, vertical turbulent intensity is higher for vegetated region, but for outer layer it is higher for non-vegetated region. It revealed that the increases in streamwise and lateral turbulent intensity throughout the flow depth in the channel, but decreases the vertical turbulent intensity at outer layer of flow depth in the channel when flow passes from non-vegetated region to vegetated region.

3.3 Turbulent kinetic energy

The flow becomes more turbulent with increasing Reynolds number according to Yagci et al. (2010). The Normalized turbulent kinetic energy k^+ (k^+ = k/U2) offers the cumulative result of u+, v+ and w+ are drawn against normalized depth of flow (Fig. 5). In Fig. 5, turbulent kinetic energy increases towards free surfaces. The result shows that the turbulent kinetic energy is higher for vegetated region than the non-vegetated region throughout the flow depth. Magnitude of normalized turbulent kinetic energy is approximately (0.011-0.017), except near the bed surface for non-vegetated region and approximately (0.013-0.020) for vegetated region, except near the bed surface. Turbulent kinetic energy increases by approximately 30% when fluid flows through vegetated region. It exposed that the emergent rigid vegetation increases the turbulent kinetic energy in the channel when flow enters in the vegetation region.

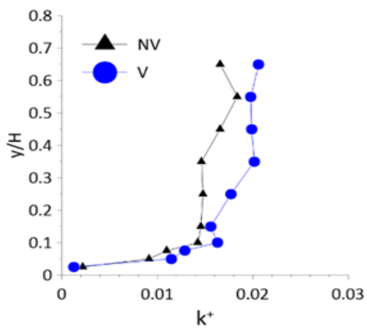

Fig. 5 Normalized turbulent Kinetic energy profile

3.4 Reynolds shear stress

The distributions of normalized streamwise-vertical, streamwise-lateral and lateral-verical Reynolds shear Stresses are uw^+, uv^+, and vw^+ ($uw^+ = u'w'/U^2$, $uv^+ = u'v'/U^2$, and $vw^+ = v'w'/U^2$) where u', v' and w' are the fluctuation of u, v and w respectively are shown in Fig. 6. In Fig. 6a, the results shows that the uw^+ is negative in nature for vegetated and non-vegetated region. It is gradually decreases towards free surface at non-vegetated region throughout the flow depth and minimum value achieved in outer layer of flow. It shows bulges near the bed surface. In the vegetated region, uw^+ is stronger in inner layer and weaker in outer layer throughout the flow depth as compared to non-vegetated region because vegetation stem offered drag resistance. It is very close to zero near the bed surface for both test section. Fig. 6b shows uv^+ in vegetated and non-vegetated region. It is negative in nature for both section except very close to the bed surface. It is maximum at near bed surface and decreases towards free surface and very close to zero near bed surface in non-vegetated region and also shows bulges in inner layer. In the vegetation region, it shows stronger magnitude for inner layer and weaker for outer layer as compared to non-vegetated region. Fig. 6c shows the vw^+ in vegetated and non-vegetated region. It is increases towards bed surface and close to zero for non-vegetated region. Magnitude of vw^+ is stronger with negative sign towards free surface. Distribution of vw^+ like a vertical straight line whose magnitude is close to zero for vegetated region. It is weaker for vegetation region as compared to non-vegetated region throughout the flow depth.

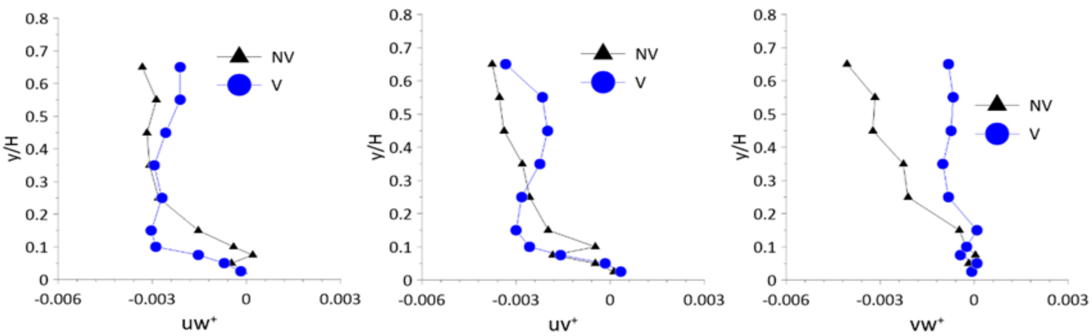

Fig. 6 Normalized Reynolds shear stress profile (a) streamwise-vertical, (b) streamwise-lateral, and (C) lateral-vertical direction

The Reynolds shear stress uw^+, uv^+, and vw^+ are relatively weaker in vegetation region as compared to non-vegetation region, which are negative in nature and close to zero near bed surface. Due to shuddering effect of the vortices, distribution of uw^+, and uv^+ near bed surface are irregular. The Reynolds shear stress decreases towards the bed surface because of the presence of viscous force, but they are being finite.

4. Conclusions

This experiment was conducted in a straight rectangular channel with emergent rigid vegetation in staggered pattern. In this paper, three-dimensional turbulence flow characteristics such as velocity, turbulence intensity, turbulent kinetic energy and Reynolds shear stress are investigated. Further the results of the vegetated region are compared and analysed with the non-vegetated region. In this study, found that the vertical distribution of streamwise velocity is decreases when flow enters in vegetated region from non-vegetated region. Transverse velocity mostly towards centre of wake in vegetated region as compared to non-vegetated region. Fluid particles moves in downward direction at non-vegetated region but it moves in upward direction at vegetated region. When fluid particle passes from non-vegetated region to vegetated region then streamwise and lateral turbulent intensity increases. In the comparison of non-vegetation region, vertical turbulent intensity in vegetated region is increases in inner layer and decreases in outer layer of flow depth. Turbulent kinetic energy is higher for vegetated region. Streamwise-vertical and streamwise-lateral Reynolds shear stress are higher for inner layer and smaller for outer layer with negative sign in vegetated region, but lateral-vertical Reynolds shear stress are always weaker for vegetated region. The presence of vegetation affects the flow behaviour in river. This study is beneficial for hydraulic structure, where vegetation growth is prominent. This investigation will be helpful for flood control, erosion control, ecological restoration and reduces the flow conveyance capacity of river. This study provides understanding of the behaviour of emergent rigid vegetation channel.

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