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Flow characteristics within different configurations of submerged flexible vegetation

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SUMMARY

The effects of three configurations (aligned, staggered, and columnar) of submerged flexible vegetation on flow structure are investigated experimentally in the laboratory. Time-averaged flow velocity and turbulence behavior are evaluated at different positions in each configuration by using a 3D acoustic Doppler velocimeter (ADV). According to the hydrodynamic regimes in experimental results, the vertical distribution of streamwise velocity can be separated into three layers—the upper non-vegetated layer, middle vegetation layer, and lower sheath layer. This three-layer model, which is associated with different logarithmic equations, can be applied to describe the vertical distribution of streamwise velocity. The local maximum velocity within vegetation occurs at the sheath section of a plant clump (0.10–0.15 vegetation height (H_v)) where the frontal width is minimal. Turbulent intensities in the streamwise (u_{rms}) and spanwise (v_{rms}) directions peak at the sheath section and at the approximate top of the canopy (0.9–1.2H_v). The maximum Reynolds stresses exist at roughly 0.9–1.2H_v, which may be migrated vertically as the frontal width of a plant clump is increased. This high frontal width also increases streamwise velocity above vegetation, leading to increase variations in Reynolds stresses around the canopy top. On the vertical turbulent velocity scale (w_{rms}), the vortices above a still canopy rotate faster than those above a waving canopy. Therefore, the experimental results demonstrate that the flow field can vary significantly at the sheath section and at the top of a plant clump due to altered flow pass. These analytical findings will likely prove useful when designing ecological habitats and preventing riverbed erosion.

1. Introduction

Vegetation in river or riparian systems have an important role in altering flow resistance and turbulence; and consequently affects the transport of sediment, nutrients, and contaminants (Fairbanks and Diplas, 1998; Luhar et al., 2008; Nepf and Vivoni, 2000; Tsujimoto, 2000; Ghisalberti and Nepf, 2005). Such changes generate various habitats and promote biodiversity (Kemp et al., 2000; Leonard and Luther, 1995). Thus, aquatic and riparian vegetation has recently garnered considerable attention in the management and restoration of rivers and costal ecologies.

Wu et al. (2005) has developed a depth-averaged two-dimensional numerical model to simulate flow, sediment transport, and bed topography in river channels with emergent and submerged rigid vegetation and large woody debris. Large eddy simulation models have been developed to effectively simulate the effects of submerged vegetation on the mean flow field (Cui and Neary, 2008). Abdeen (2008) and Wu et al. (2009) have demonstrated that the artificial neural networks models are able to predict the open-channel flow. Li and Zhang (2010) developed a 3D model to investigate the hydrodynamic and mixing processes generated by the wave-vegetation interaction under regular and random waves.

Nepf and Vivoni (2000) noted that wake turbulence generated by vegetation stems is closely related to the submergence depth. Nezu and Onitsuka (2001) demonstrated that horizontal vortices near a free surface are caused by the inflection of shear instability and turbulence near the free surface is transported laterally from the non-vegetation zone toward the vegetation zone by secondary currents. Maximum turbulence intensity and Reynolds stress occur approximately at the maximum deflected plant height (Nezu and Sanjou, 2008; Ghisalberti and Nepf, 2009). Wilson et al. (2003) investigated the effects of submerged flexible vegetation forms on turbulence structure, indicating that vegetation with many fronts provides good protection from scouring and erosion. The existence of a momentum exchange between the two layers within and above the top of vegetation results in difficulties when analyzing the vertical distribution of mean velocity (Huai et al., 2009; Wilson, 2007).

The streamwise velocity profile distributed within the submerged vegetation is principally affected by vegetation drag, resulting in complex flow conditions (Huai et al., 2009; Wilson,

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Nomenclature

U_F	vertical velocity distributions of fully developed flow measured at 4 m from the upstream inlet (cm s^{-1})
U_0	mean flow velocity of U_F (cm s^{-1})
x, y, z	streamwise, spanwise, and vertical coordinates, respectively
H	water depth (cm)
H_v	undisturbed vegetation height (cm)
H_p	distance from bed surface to the inflection point (cm)
H_s	vertical distance from bed surface to the location of maximum velocity in the sheath section of a plant (cm)
H_u	water depth where Reynolds stress is becoming <10% of the maximum Reynolds stress below the top of the canopy (cm)
H_m	water depth at the maximum Reynolds stress (cm)
H_r	water depth where Reynolds stress starts to move close to zero above the canopy y (cm)
u, v, w	mean velocity components in streamwise, spanwise, and vertical directions, respectively (cm s^{-1})
u', v', w'	turbulent velocity components in streamwise, spanwise, and vertical directions, respectively (cm s^{-1})
u_{rms}, v_{rms}, w_{rms}	root mean squared (*rms*) velocity (also named turbulence intensity, i.e. $\psi(\overline{u'^2})^{1/2}$ ... $\psi(\overline{v'^2})^{1/2}$ ... $\psi(\overline{w'^2})^{1/2}$ Z) in streamwise, spanwise, and vertical directions, respectively (cm s^{-1})
$--\overline{u'v'}$	Reynolds shear stress in vertical direction (z) on plane perpendicular to streamwise direction (m $s^{-1})^2$
$-\overline{u'v'}$	Reynolds shear stress in spanwise direction (y) on plane perpendicular to streamwise direction (m $s^{-1})^2$
$-\overline{v'w'}$	Reynolds shear stress in streamwise direction (x) on plane perpendicular to spanwise direction (m $s^{-1})^2$
d_c	canopy density (cm^{-1})
V	canopy volume (cm^3)
W_d	frontal width of a clump plant (cm)
δ	penetration depth (cm)

2007; Zhang and Nepf, 2009). The velocity profile of submerged vegetation flow was generally divided into two layers or three layers (Cheng, 2007; Huai et al., 2009; Klopstra et al., 1997; Neary, 2003; Pietri et al., 2009; Righetti and Armanini, 2002). The shear velocity or the averaged vegetated layer (cross section) velocity has been applied in the logarithmic (Stephan and Gutknecht, 2002; Järvelä, 2005; Baptist et al., 2007; Yang et al., 2007; Nezu and Sanjou, 2008) or power law (Montes, 1998; Chanson, 2004; Cheng, 2007) to accurately describe the velocity profile in the upper layer above the tops of vegetation. Järvelä (2005) defined a new calculation of shear velocity based on mean deflected plant height to enhance practical applicability without the need for complex turbulence measurements. However, the shear velocity or the averaged vegetated layer velocity is easily altered by vegetation deflection and water depth due to different vegetation configurations and the irregular channel bed.

Circular cylinder rods have been utilized as vegetation elements in numerous flow structures studies (Finnigan, 2000; Poggi et al., 2004; Raupach and Thom, 1981); however, flow over flexible vegetation differs from flow over rigid vegetation (Ghisalberti and Nepf, 2006). The effects of vegetation density and configuration patterns on canopy turbulence have also been investigated (Finnigan, 2000; Green et al., 1995; Nezu and Sanjou, 2008; Pietri et al., 2009; Poggi et al., 2004). Nezu and Sanjou (2008) allocated different streamwise and spanwise spacings between closely grouped vegetation elements to investigate the effects of submergence depth on turbulence. Pietri et al. (2009) investigated flow behavior among vegetation elements with an aligned array and a staggered array. However, these studies described velocity and turbulence intensity profiles by spatially averaging values in the spanwise direction (cross section), which may not represent the flow condition for a specific location.

Although many studies have investigated flow characteristics in vegetated open-channel flows, the flow and turbulence profiles within submerged flexible vegetation for a specific location remain unclear. The primary objective of this study is to investigate the effects of vegetation spacings and configurations on the flow structure within submerged flexible vegetation at a specific location. Thus, the flow velocity, Reynolds stress, and turbulence intensity across various water depths at different measurement positions in different vegetation configurations were investigated and compared. The average of streamwise velocity distribution of the fully developed flow instead of shear velocity was incorporated into the logarithmic-law to assist in explaining flow velocities varied with different vegetation configurations.

2. Materials and methods

2.1. Experimental apparatus and conditions

Experiments were conducted in a rectangle and linear glass-walled flume 8 m long, 0.6 m high, and 0.3 wide. The flume, which have an adjustable slope, is located at the Stream Morphology and Engineering Laboratory, National Chung-Shing University, Taiwan. The flume primarily consists of a head tank, a channel, and an interior recirculating system. Flow discharge is controlled by an electrical magnetic valve and an adjustable weir system at the water flume end.

Based on a discharge of 0.0153 m^3/s, the approaching flow depth and velocity were maintained at 25.3 cm and 20.2 cm/s, respectively. The flow depth was designed to about twice as high as vegetation height (12 cm). The Froude number and Reynolds number calculated based on flow depth were 0.13 and 50,902, respectively. A three-dimensional sideways 16-MHz macro-acoustic Doppler velocimetry (MacroADV) (SonTek, San Diego, CA, USA) was utilized to measure velocity and turbulence of each measurement point at a sampling frequency of 10 Hz with 30 s sampling time. Therefore, 300 data were acquired to calculate the average value for each measurement point. Measurements could not be taken in the region 50 mm below the water surface due to ADV limitations. The transmitting transducer emitted an acoustic wave through the water to the measurement point and receiving transducers determined flow velocity when the reflected signal was received. The seeding material consisted of hollow glass spheres with a mean diameter of about 10 μm (SonTek, USA) was added to water to reflect the pulse. Velocity uncertainty was 0.1 cm/s. The flow images were taken by a PULNiX TM-6740GE camera (640 × 480 pixels) at a frame rate of 200 Hz.

2.2. Vegetation materials and configurations

Flexible plastic materials were chosen to mimic aquatic vegetation. The diameter and length of the single flexible material were