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Hydrodynamics of discontinuous rigid submerged vegetation patches in open-channel flow

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Abstract

We investigate the effects of discontinuous rigid submerged vegetation patches on flow turbulence. Two laboratory flume experiments are performed to validate the large eddy simulation (LES) model. The obtained LES data are in good agreement with the experimental data. They are also highly accurate in capturing the secondary peaks of the mean velocity near the channel bed. The coherent vortices, which are generated by the shear between the slower canopy flow and the faster overlying flow, are associated with the velocity inflection and maximum Reynolds stress around the interface. The mean velocity in the gap regions is evidently slower than that in the canopy regions. A high canopy density and Reynolds number are more conducive for the fully developed flow state of discontinuous vegetation patches. The velocity distinctly increases within the first two patches with a high canopy density. The velocity profile in the large gaps is more stable than that in the small gaps below the vegetation height, whereas the effect of patch distribution is not evident in the overlying flow layer. A spectral analysis shows that two vortex scales, namely, stem-scale and shear-scale vortices, influence the turbulence of flow through discontinuous vegetation patches. The power spectral densities are consistent with Kolmogorov theory for a −5/3 slope when the dominant eddy frequency exceeds 0.04 Hz.

Keywords: Discontinuous vegetation patches; Large eddy simulation; Secondary peak; Spectral analysis

1. Introduction

Vegetation in natural rivers is distributed in patches that interact with water flow in a strongly nonlinear manner. The growth patterns of such patches are influenced by flow. Conversely, these patches alter flow by affecting flow resistance, bed shear stress, sediment transport, water quality, and wave energy (Maltese et al., 2007; Nepf, 1999; Sand-Jensen and Vindbæk Madsen, 1992; Sukhodolov and Sukhodolova, 2010; Zeng and Li, 2014). Horizontal advection and vertical turbulent mixing caused by vegetation patches play key roles in ecological functions, such as in food supply, food distribution, and the physical environment of aquatic organisms (Folkard and Gascoigne, 2009; Murray et al., 2002; Riisgard et al., 2007; Simpson et al., 2007; Widdows and Navarro, 2007).

Cotton et al. (2006) and Naden et al. (2006) studied the influence of vegetation distribution on mean velocity and turbulence characteristics in specific natural channels. Neumeier (2007) measured velocity and turbulence variations at the edge of saltmarshes. He speculated that a large vertical velocity and a high turbulence at the edge of saltmarshes might reduce sediment deposition on top of the vegetation zone. Maltese et al. (2007) conducted a quadrant analysis and found an ejection-dominated upper layer, which was a sweep-dominated region around the top of the canopy and within the gaps. They found no dominant quadrant within the canopy. Sukhodolov and Sukhodolova (2010) and Maltese et al. (2007) focused on the spatial patterns of turbulent structures that developed over submerged vegetation patches. Bouma et al. (2007) analyzed spatial sedimentation and erosion patterns within vegetation patches through field and flume experiments. They also assessed the relevance of hydrodynamic flume studies for long-term sediment dynamics. Siniscalchi et al. (2012) examined the effects of aquatic vegetation on flow turbulence, drag forces, and flow–drag interrelations in a finite-size characteristic patch. The turbulent energy increased close to the leading edge and along the patch canopy top, where the turbulence shear was enhanced. In the present study, a numerical simulation using the large eddy simulation (LES) model was performed on flows through

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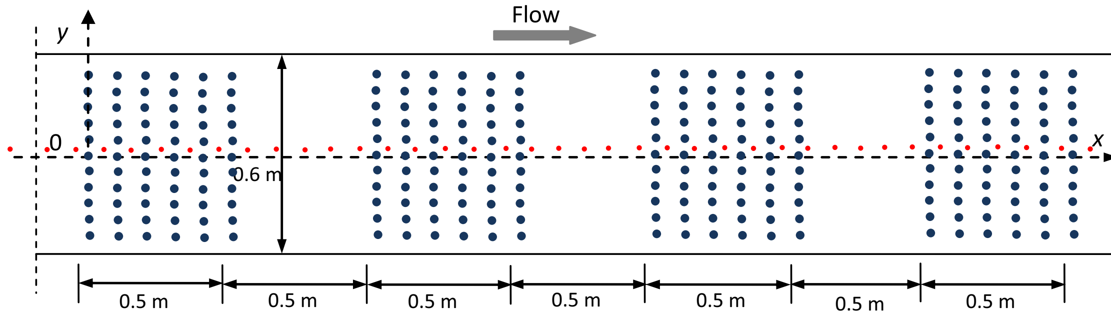

Fig. 1. Plan view of patch arrangement (Case A). The red dots represent the vertical profiles in which ADV measurements were made. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

discontinuous rigid submerged patches. The LES model has been successfully applied to submerged rigid vegetated flows (Cui and Neary, 2002, 2008; Stoesser et al., 2006, 2009). However, the performance of this model in discontinuous rigid submerged vegetation patches in terms of flow turbulence has not yet been thoroughly investigated. The detailed laboratory flume measurements of the instantaneous velocity were obtained using an acoustic Doppler velocimeter (ADV). The experiment result was used to determine the longitudinal variation in the mean velocity and turbulence characteristics as well as to validate the LES numerical model. Two vegetation densities, flow velocities, and distribution forms were selected following previous research (Bouma et al., 2007; Liu et al., 2008; Stoesser et al., 2009; Zeng and Li, 2014).

The objectives of this study are as follows:

1. To compare the LES results with the experimental measurements and to evaluate the performance of LES in terms of the interactions between discontinuous rigid submerged vegetation patches and open-channel flows;
2. To analyze the mean velocity profiles and turbulence characteristics of flows through discontinuous rigid submerged patches using LES;
3. To investigate the influence of canopy density, Reynolds number, and distribution form on flows through discontinuous rigid submerged patches.

2. Methods

2.1. Experimental facility and experimental conditions

Experiments were conducted in a 20 m long, 0.6 m wide, and 0.4 m deep glass flume in the Hydraulics and Fluid Mechanics Laboratory at Wuhan University. The bed slope was fixed at 0.2%. The flow was made uniform by modifying the tailgate at the downstream end of the flume. PVC baseboards (1 m × 0.6 m × 0.01 m) were used to cover the entire bottom of the flume. Rigid cylinders (8 mm diameter, 25 cm height) were used to simulate rigid vegetation. Fig. 1 shows the experimental setup and coordinate system. The x-axis is the streamwise direction, with $x = 0$ at the leading edge of the patch. The y-axis is the spanwise direction, and $y = 0$ is the center line of the flume. The z-axis is the vertical direction, and $z = 0$ is the channel bed. The different configurations are summarized in Table 1.

We used Cheng (2011) as our primary reference for vegetation density. In Appendix A of Cheng (2011), 277 and 103 data sets were collected for the cases of rigid vegetation and flexible vegetation, respectively. A density of 254 m^{-2} was selected based on typical floodplain vegetation, such as reed canary grass, great bulrush, and herbaceous vegetation (Baptist, 2005; Meijer, 1998a, 1998b; Van Velzen et al., 2003). The density of 423 m^{-2} was based on the flume experiments of Murphy et al. (2007) and Stone and Shen (2002).

Velocity was measured using a 3D ADV. The sampling frequency was 50 Hz. The measurements of the velocity at each point within the $y = 2.5$ cm vertical section (Fig. 1) were taken for 160 s, including a total of 8000 samples. The data samples with signal correlations below 70% and signal-to-noise ratios less than 10 were filtered out. The measuring points were located at 10 cm intervals downstream, every 1 cm vertically above the bed (Fig. 2), starting at 80 cm upstream from the first patch edge.

2.2. LES mathematical model

LES is a mathematical model for turbulence used in computational fluid dynamics. This model was initially proposed by Smagorinsky (1963) to simulate atmospheric air currents.

Table 1
Hydraulic conditions. Q is the discharge, H is the water depth, U is the initial average velocity, N is the vegetation density, L is the gap length, h is the cylinder height, l_w is the characteristic length, l_i is the length of the intrusion region, R_e is the Reynolds number and R_{e*} is the cylinder Reynolds number.

Case	Q (L/s)	H (m)	U (m/s)	N (1/m^2)	L (m)	h (m)	l_w (m)	l_i/l_w	R_e ($=UH/\nu$)	R_{e*} ($=Ud/\nu$)
A	25.92	0.36	0.12	254	0.5	0.24	3.5	0.11	42900	953
B	25.92	0.36	0.12	423	0.5	0.24	6.35	0.09	42900	953
C	54	0.45	0.2	423	0.5	0.24	8.47	0.07	89374	1589
D	25.92	0.36	0.12	254	1.1	0.24	6.99	0.04	42900	953