Geomorphology 204 (2014) 314–324

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Flow characteristics in different densities of submerged flexible vegetation from an open-channel flume study of artificial plants

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ARTICLE INFO

Article history:
Received 28 December 2012
Received in revised form 11 August 2013
Accepted 14 August 2013
Available online 30 August 2013

Keywords:
Flow velocity
Reynolds stress
Turbulence intensity
Manning coefficient
Submerged artificial plants
Open-channel flume

ABSTRACT

The effect of submerged flexible vegetation on flow structure (e.g. flow velocity, Reynolds shear stress, turbulence intensity and Manning coefficient) was experimentally studied with a 3D Acoustic Doppler Velocimeter (ADV) in an open-channel flume. The results from flow observations over artificial plants (designed to simulate natural vegetation) showed that flow structure was affected markedly by the presence of submerged flexible vegetation. The study provides understanding of flow patterns, variation in velocity profile and turbulence structures that are affected by plant stem density. The study also reveals how the flow patterns return to stability at the downstream end of the vegetated area which is critical in determining the length of the vegetated areas for restoration cases. Also, new mathematical expressions (equations) have been formulated to clearly express variations in velocity profile, Manning coefficient and flow discharge ratio with vegetation density. Vertically, the velocity profile could be roughly divided into three layers, including the upper non-vegetated layer, the middle canopy layer, and the lower sheath layer. In the upper non-vegetated layer, velocity profiles followed the logarithmic law, and a corresponding empirical equation was developed based on the observed data. The flow is from left to right in this study, and the velocity profile followed a left round bracket "(" with the minimum point located at the canopy area ($0.7H_v$, where H_v denotes vegetation height) within the middle canopy layer. However, the velocity profile followed a right round bracket ")" in the lower sheath section layer with the maximum point located at the sheath section ($0.2H_v$). With increasing vegetation density, the velocity and corresponding flow rate increased in the upper non-vegetated layer and decreased within the middle canopy layer and the lower sheath layer. The ratio of average flow discharge in the non-vegetated and vegetated layers followed the exponential function law with increasing vegetation density. This analysis revealed the effect of vegetation on flood potential and flow bottom scour. Reynolds stresses peaked above the canopy top ($z/H_v = 1.0$–1.2, here z denotes vertical coordinate), and the turbulence intensities reached their maximum peak at two locations including the sheath section ($z/H_v = 0.1$–0.4) and the canopy top ($z/H_v = 1.0$–1.6) for all vegetation densities. Manning coefficient was highly correlated to vegetation density and inflow rate with new empirical equations being proposed.

1. Introduction

Vegetation plays an important role in altering flow characteristics (such as flow velocity, Reynolds stress, turbulence intensity and Manning roughness coefficient) compared with non-vegetated conditions in lakes and rivers. Such variations influence the hydrodynamics of the flow field. The presence of in-channel vegetation is sometimes regarded as a problem because it can reduce flow capacity, with implications for flooding. Flume experiments have demonstrated that vegetation alters flow structures and enhances sedimentation (Leonard and Croft, 2006). These changes substantially affect nutrient and contaminant transport, and also greatly contribute to sediment resuspension and bank erosion (Järvelä, 2002). Thus, vegetation is a key factor in sediment transport, flow connection and geomorphology in rivers and lakes (Tsujimoto, 1999). Furthermore, parameters commonly used in numerical hydrodynamic simulations, such as Manning coefficient, are strongly impacted by vegetation (Noarayanan et al., 2011). Hence, investigating the impact of aquatic vegetation on flow characteristics is of substantial importance in river and lake management and restoration. Moreover, investigations such as these provide a foundation for further study on sediment erosion and mass transport (Wu et al., 1999).

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http://dx.doi.org/10.1016/j.geomorph.2013.08.015

The impact of vegetation on commonly measured flow parameters is related to plant structure, such as the distribution of sheath, branches and leaves (Hui and Hu, 2010). In addition, the impact of plants on flow parameters varies with the flexibility and structure of plants. For example, Wilson et al. (2003) mentioned that the turbulence intensity and drag force induced by rods with front foliages attached are larger and fluctuated more than that by rods without front foliages. Previous studies have divided the velocity profile into two or three layers: the upper non-vegetated layer, and the middle and bottom layers with vegetation (Klopstra et al., 1997; Righetti and Armanini, 2002; Neary, 2003; Cheng, 2007; Huai et al., 2009a; Pietri et al., 2009; Chen et al., 2011). Klopstra et al. (1997) simply divided the layers into vegetation layer and surface layer. Cheng (2007) divided the layers into viscous sublayer, overlap region and wake zone by velocity profile shape. The thickness and location of the three layers changed under different vegetation densities, depths and configurations. Järvelä (2005) carried out an experimental study with natural submerged flexible wheat plants and found that the flow structure above the submerged flexible part (the upper layer) follows the log law and that the maximum velocity occurs at the maximum deflected plant height. Liu et al. (2010) found that velocity within the canopy is nearly constant and that velocity increases substantially above the canopy top towards the free water surface.

Huai et al. (2009a) found that Reynolds shear stress reached the peak value around the canopy top, and decays to a relative uniform value for flow depths from the peak value to the free water surface or the bottom bed, respectively (Nepf and Vivoni, 2000; Huai et al., 2009a; Hossein et al., 2011). The maximum velocity is located at the location of zero Reynolds shear stress (Hossein et al., 2011). Cui and Neary (2008) noted that the impact of vegetation on turbulence intensity is related to the submerged depth. Leonard and Croft (2006) found that the presence of plants damps large-scale eddies, which impacts turbulence structure within the vegetated canopy. Hossein et al. (2011) showed that the maximum turbulence intensity is located at the inflection point of the plant stem when swaying. The vertical exchange of mass and momentum between the non-vegetated layer and the vegetation canopy influencing both the mean velocity and turbulence makes it difficult to analyze and explain the measured data provided by the vertical profiles (Huai et al., 2009a). Noarayanan et al. (2011) found that vegetation density, diameter, flexibility and height are all affect the Manning coefficient. However, the flexibility of vegetation is difficult to measure (Fathi-Moghadam and Kouwen, 1997). Hence, the vegetation flexibility was not considered in this study; instead flow behavior was studied over various densities of artificial plants. Although previous studies have identified that vegetation has an important impact on flow characteristics, there exists little detailed analysis of the relationship between flow structure and variation in vegetation density. This study was motivated in part by the need for a detailed understanding of how the flow patterns in rivers and channels are impacted differently by changes in vegetation density.

The objectives of this study were to investigate the impact of submerged artificial plants on the flow structure with different densities at different stream-wise positions within a channel flume. In addition, the equations for describing the flow structure in different vegetation densities associated with the submerged height, and water depth were determined. The profiles of flow velocity, Reynolds shear stress and turbulence intensity were also investigated and compared, and the relationships between Manning coefficient and vegetation density at different flow rates were studied.

2. Materials and methods

2.1. Experimental apparatus and conditions

The experimental system (Fig. 1) was composed of two pumps to force water through the system and maintain recirculation, an inlet section with turning valves at the upstream end to control the flow discharge and generates fully developed turbulent flow, a major test section with a re-circulating open-channel rectangle flume to control interactions between overflow and vegetation, and an outlet section with a triangular adjustable weir at the downstream end to control the water level. The flume was 30.0 m long, 0.5 m wide and 1.0 m high with glass-sidewalls and a concrete bottom so that the interactions between the vegetation and flow could be observed clearly. The water levels were kept at approximately 0.5 m with two fixed flow rates of Q = 0.06 and 0.025 m^3/s. The corresponding mean stream-wise velocities of fully developed non-vegetated flow were $u_o = 24$ and 10 cm/s, which are within the general minimum and maximum velocity range of most channels during the growing season of vegetation in eastern China (Yan et al., 2011).

A three dimensional sideways Macro-Acoustic Doppler Velocimetry (ADV) (SonTek, San Diego, CA, USA) was used to measure the instantaneous velocity and turbulence along the vertical direction at various sections at a frequency of 20 Hz with a 30 s sampling time. From control runs conducted prior to the experiment, it was revealed that this duration for sampling was satisfactory for determining accurate turbulence statistics. Thus, a total of 600 data measurements were collected at each location. With a post-treatment software, WinADV (Wahl, 2000), the average velocity and turbulence values were processed and obtained. Measurements at 50 mm below the surface could not be taken due to ADV limitations. For more information about the

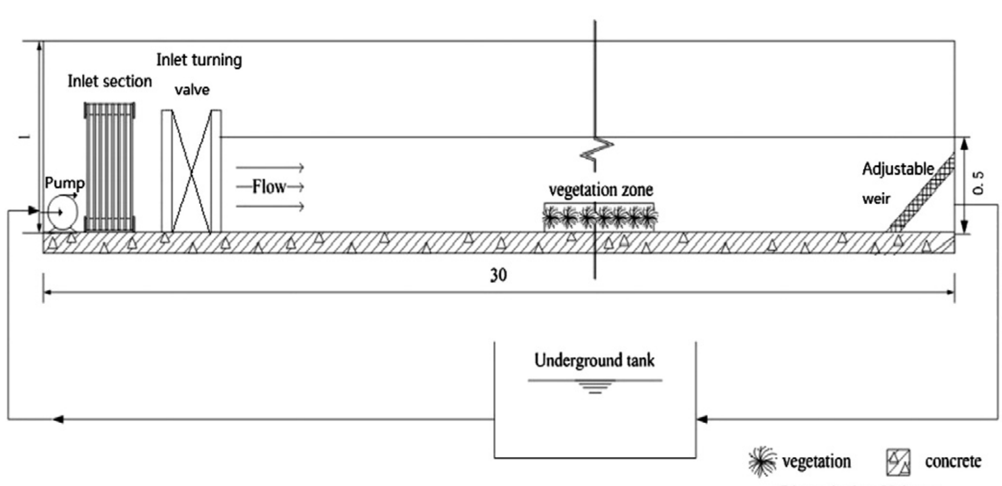

Fig. 1. Side view of the experimental re-circulating open-channel rectangle flume setup.