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Experimentation on submerged flow over flexible vegetation patches with downward seepage

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ABSTRACT

The present study addresses the change in flow characteristics of alluvial channel occupied by submerged vegetated patches of different spacing under downward seepage condition. Measurements show that velocity measured at upstream vegetation section is reduced in the range of 8–16% as the flow reaches the downstream vegetation section. An increase in the near bed velocity and Reynolds stresses has been observed with the application of downward seepage. Reynolds stress profiles show that the maximum value exists near the top of the patches. When the flow enters the vegetation section, more erosion takes place at the upstream vegetation section and then decreases along the downstream section. The maximum turbulence intensities lie near the vegetation top and the turbulence created at the upstream vegetation section is reduced in the range 4–9% as the flow reached the downstream vegetation section. The presence of vegetation induces a local effect which leads to occurrence of erosion and deposition in the vegetated section. Third order moments highlights the downward seepage effect on increasing the flux transport in downward direction and diffusion in the streamwise direction which is shown by the governance of sweep event over ejection event from quadrant analysis. Drag coefficient decreases with the application of downward seepage. The experiments have resulted that vegetation can provide considerable stability to channels by reducing channel erosion even with downward seepage.

1. Introduction

The presence of vegetation is one of the factors that change the mean and turbulent flow field in a channel (Nepf, 2012a). Aquatic vegetation in conveyance channels increases the flow resistance thereby reducing the conveyance capacity and was traditionally regarded as a nuisance and hence it was removed from channels to increase the passage of flow (Kouwen, 1992; Wu et al., 1999). The vegetation along the bed of rivers plays an important role on the hydrodynamic behavior, on the ecological equilibrium and on the characteristics of the river (Wilcock et al., 1999; Mars et al., 1999; Lee and Shih, 2004; Pollen and Simon, 2005; Turker et al., 2006; Zhu et al., 2016). The presence of vegetation canopies in rivers has recently been regarded as one of the key measures for water management and river environment, and therefore, it is necessary to the flow structures in a vegetative channel (Poggi et al., 2004; Ghisalberti and Nepf, 2006; Tanino and Nepf, 2008). Different materials have been used for imitating aquatic vegetation such as wooden cylindrical dowels or rods (Stone and Shen, 2002; Liu et al., 2008; Poggi et al., 2004), flexible strips or blades (Nepf and Vinoni, 2000; Chen et al., 2011) and natural vegetation (Järvelä, 2002; Stephan and Gutknecht, 2002; Carollo et al., 2005). In comparison to studies related to rigid vegetation types, there have been a fewer number of investigations on flow in channels with flexible vegetation (Wilson et al., 2003). Huai et al. (2009) have carried out an experimental study on flow with submerged flexible vegetation and found that the presence of vegetation influences the distributions of the streamwise velocity and the Reynolds stress. Turbulence intensity and Reynolds stress reach the maximum value near the top of the vegetation. A new velocity distribution based on mixing length approach is developed. Chen et al. (2011) have studied the flow structures of fully submerged flexible vegetation with different configurations and different spanwise and streamwise spacing. The whole flow region is divided into three regions: upper non-vegetated region, middle vegetated layer and lower sheath layer. The flow field can be altered at the sheath section and at the top of the plant clump where the flow is retarded by plant or flow changed suddenly. Nepf et al. have conducted systematic studies involving combining experiments with the theory of turbulence and stated that the turbulence is greatly related to vegetation characteristics (Nepf, 1999; Finnigan, 2000; Finnigan

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et al., 2009; Nepf, 2012a). Nepf and Vinoni (2000) have investigated experimentally the effect of water depth on turbulence structure, and observed that the generation of wake turbulence because of vegetation stems is dependent of relative submergence depth. The importance of analyzing the flow characteristics and appraising the resistance offered by the vegetation has been a primary problem among researchers (Cowan, 1956; Chow, 1959; Petryk and Bosmajian, 1975). The hydraulic conditions in a vegetated channel are determined by the drag imposed by the vegetation stems. Drag coefficient is frequently used as a parameter for representing the flow resistance (Stone and Shen, 2002; Thompson et al., 2004; Armanini et al., 2005). A series of experiments have been conducted for simplifying the flow phenomenon and simulate the roughness coefficient and drag force (Darby, 1999; Noaranayan et al., 2012) to study the flow characteristics in a vegetative channel. Nepf (1999) have developed a model to describe the drag, turbulence and diffusion for flow through emergent vegetation and covered the natural range of vegetation density and stem Reynolds numbers to extend the cylinder-based model for vegetative resistance by including the dependence of the drag coefficient, stem density and highlight the importance of mechanical diffusion in vegetated flows. Siniscalchi et al. (2012) investigated the effects of a finite-size vegetation patch on flow turbulence, variations in drag forces experienced by individual plants within the patch, and flow-drag interrelations. Reynolds stresses found within the patch reflect the influence of plant morphology, which affects the shape of the longitudinal velocity profile and associated turbulent fluxes.

Alluvial channels have permeable boundaries made of sediment particles in natural rivers and irrigation channels. Flow in natural channels is a complex phenomenon as water is continuously seeping in or out of the channel depending on the water levels in the channel and the surrounding groundwater table. Tanji and Kielen (2002) have estimated that seepage losses in semi-arid regions can account for 20–50% of the total flow volume in unlined earthen canals. Kinzli et al. (2010) and Martin and Gates (2014) have measured loss of water around 40% and 15% because of downward seepage. Apart from losses, the downward seepage leads to a change in bed deformation conditions and affects the hydrodynamic behaviour of the channel (Richardson et al., 1985; Maclean, 1991; Ramakrishna Rao et al., 1991; Chen and Chiew, 2004; Deshpande and Kumar, 2015; Patel et al., 2015).

Although there have been previous research on vegetation-flow interaction considering a single vegetation stem, the flow characteristics in a vegetation patch occurring in groups of stems is not yet known. Vegetation stems occurring in groups can be found in natural conditions and the hydrodynamic conditions for such case are important to explore for river restoration projects. In order to address the highlighted knowledge gaps, the present study explores the interactions between an alluvial channel and a finite-size patch constructed of grouped artificial flexible plants. Downward seepage occurring in natural or alluvial channels is being considered in the present study. Present research focuses the changes in the flow velocity distribution, Reynolds stress and turbulence intensities in a vegetated channel with downward seepage through a series of experiments conducted using artificial vegetation patches. Quadrant analysis and moment analysis have also been calculated to understand the flow characteristics. Knowing the importance of drag imposed by the vegetation patches, the effect of downward seepage on drag coefficient is also calculated.

2. Experimental methodology

Different experiments were conducted in a tilting flume with 20 m in length, 1 m in width, and 0.72 m deep. A tank of dimensions 2.8 m long, 1.5 m wide and 1.5 m deep was provided at the upstream of the flume to straighten the flow prior to its introduction in to the flume. Two metres of upstream length of the main channel bed was made non-porous and the remaining length of the channel was made porous by covering a fine mesh (0.1 mm). This mesh arrangement was supported by steel tube structure of 0.22 m height which was placed on the bottom of the bed. Bottom pressure chamber (15.20 m in length, 1 m wide and 0.22 m deep) were formed by the area between the bottom of the channel and the fine mesh. Sand was placed on the fine mesh in order to prevent its entrance into the bottom chamber. This pressure chamber was used to remove the water from the main channel through the sand bed in perpendicular direction. In order to prevent highly turbulent flow from entering the channel, a wooden baffle is installed at the upstream collection tank and the main channel has been smoothened for a length of 2 m at upstream. The bed slope was fixed at 0.15% which was kept fixed for all the experiments. The flow in the flume was driven by three 10HP centrifugal pump. The discharge in the flume was measured with the help of a rectangular notch located at the downstream of the flume. The water depth in the flume was measured with a digital point gauge (resolution of 0.01 mm). Two electromagnetic flow-meters (accuracy of ±0.5%) installed at the downstream of the flume have a control valve and a digital display which is used for applying desired percentage of seepage discharge. Instantaneous velocity measurements were taken with the help of Nortek 3D Acoustic Doppler Velocimeter (ADV). Fig. 1 shows the schematic diagram of the experimental setup.

Table 1
Table showing different experimental conditions.

	Pattern	s_v (m)	S	Q_i (m^3/s)	% of seepage
1	Staggered	0.15	0.0015	0.0326	0
2	Staggered	0.15	0.0015	0.0326	10
3	Staggered	0.15	0.0015	0.0326	15
4	Staggered	0.10	0.0015	0.0326	0
5	Staggered	0.10	0.0015	0.0326	10
6	Staggered	0.10	0.0015	0.0326	15

Existing literature (Järvelä, 2005; Poggi et al., 2004; Ghisalberti and Nepf, 2006; Liu et al., 2008) on submerged vegetation did not suggest specific criteria for fixing the flow depth in a laboratory channel. Thus, in the present study the incipient motion or threshold channel criteria was used for defining the flow depth for a particular sand diameter, d_{50} = 0.418 mm. Yalin's incipient motion criteria (1972) was used for the present study and it was achieved at a flow depth (H) of 12 cm when measured at the centre of the test section and discharge (Q_i) of 0.0326 m^3/s after verifying with the help of Shields diagram. Yalin (1972) proposed a term 'ε' in which its value determines the critical condition of bed movement. 'ε' is given by

$$\varepsilon = \left(\frac{m}{At}\right)\sqrt{\frac{\rho {d_{50}}^5}{\gamma_s}} \quad (1)$$

where m is the number of detachments, A is the observation area, t is the time, d_{50} is the median diameter of grains, Υ_s is the submerged specific weight of the grains and ρ is the specific density of the fluid. Theoretically the value of ε should be zero but for practical purposes, Miller et al. (1970) recommended a value of 10^{-6}. During experiment, it had been tried to keep the value of ε close as possible. The flow Reynolds number for the given flow condition was 1.3×10^5. Then, the water surface slope was taken with the help of Pitot tube and digital Manometer Assembly (accuracy of ±0.5%). The experimental conditions are given in Table 1. The flow depth and discharge corresponding to threshold channel were maintained for further experiments with vegetation. The vegetation zone was located in the middle of the flume covering an area of 5 m long and 1 m wide (Fig. 1).