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Turbulent flow statistics of vegetative channel with seepage

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ABSTRACT

The present study is carried out for studying the impact of submerged, flexible vegetation in a channel where downward seepage occurs. Laboratory experiments on artificial vegetation of two different heights, 8 cm and 6 cm, were conducted for no-seepage, 10% seepage and 15% seepage cases. Vegetation height is an important parameter in influencing the flow characteristics in a vegetated channel, where velocity is reduced near the top of the vegetation. Results show that velocity measured at upstream vegetation section is always higher than the downstream section even with the application of downward seepage. The maximum value of Reynolds stress occurs near the top of the vegetation. When the flow enters the vegetation section, the local effect of the presence of vegetation on sediment transport is more at the upstream vegetation section and then decreases which is shown by higher Reynolds stress at the upstream as compared to downstream vegetation section highlighting the importance of vegetation in providing as an erosion control. The maximum Reynolds stress at no seepage is increased by a percentage of 17% for 10% seepage and average of 30.5% for 15% seepage. The turbulence intensities at no seepage are increased by an average value of 15% for 10% seepage and 25% for 15% seepage. The reduction of Reynolds stress and turbulent intensities along the longitudinal direction implies the importance of using vegetation as a river restoration measure providing considerable stability to channels. Third order moments highlight that downward seepage increases the streamwise flux and decreases the upward flux.

1. Introduction

Aquatic vegetation in conveyance channels increases the flow resistance thereby reducing the conveyance capacity and has traditionally been regarded as a nuisance and hence it has been removed from channels to increase the passage of flow (Kouwen, 1992; Wu et al., 1999). But it is known that submerged canopies can have a positive impact on water quality by removing Phosphates and Nitrates poured into the rivers (Velasco et al., 2003). In addition, vegetation is known to increase bank stability, reduce erosion, provide habitat for aquatic life, attenuate floods, increase aesthetic values and filter pollutants. The impact of vegetation on flow depends not only on the channel characteristics but also on the vegetation characteristics. Based on the relationship between flow conditions and vegetation characteristics, aquatic vegetation can be classified as flexible and rigid or submerged and emergent vegetations. Previous researchers carried out a large number of researches on experiments using artificial and natural vegetation in flume (Meijer and Van Velzen, 1999; Stephan and Gutknecht, 2002; Jarvela, 2002; Righetti and Armanini, 2002), on analytical approaches for vertical velocity profile (Klopstra et al., 1997; Huthoff et al., 2007; Yang and Choi, 2010), on turbulence characterization for submerged rods and vegetation (Lopez and Garcia, 2001; Nepf and Vivoni, 2002) and on numerical approaches (Kutija and Hong, 1996; Simoes and Wang, 1997; Darby, 1999). Nezu and Onitsuka (2001) conducted turbulence measurements in partly vegetated open-channel flows and found that the horizontal vortices near the free surface are generated by the inflexion shear instability and that turbulence near the free surface is transported laterally from the non-vegetation zone towards the vegetation zone by secondary currents. Wilson et al. (2003) studied turbulence structure around two different forms of submerged vegetation and concluded that the additional superficial area of the fronds affects the momentum transfer between the vegetated region and the upper flow region thereby reducing the shear generated turbulence. Chen et al. (2011) 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.

The river bed condition also plays an important role in influencing the flow characteristics. It is known that for natural channels, water percolates in the form of seepage through boundaries of alluvial channels, rivers and streams because of porosity of the granular material and difference in water level in the stream and ground water table. Based on the difference in water level between the channel and the surrounding ground water, water seeps into (upward seepage) or out of the channel bed and channel banks (downward seepage). The presence of downward seepage leads to increase in bed shear stress and sediment

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transport which consequently changes the hydrodynamic characteristics of the channel (Rao and Sitaram, 1999; Dey et al., 2011; Rao et al., 2011; Cao and Chiew, 2014; Deshpande and Kumar, 2015; Patel et al., 2015). The loss of water in the form of downward seepage in many alluvial channels constitute about 45% of the water supplied at the head of the canal and varies from 0.3 to 7 m^3/s per million square metres of wetted area (Shukla and Misra, 1994). Tanji and Kielen (2002) 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) measured loss of water around 40% because of downward seepage. Martin and Gates (2014) estimated loss of about 15% of the upstream flow rate because of downward seepage. Maclean and Willetts (1986) found experimentally that the bed shear stress increases when suction was applied over a submerged type of river intake. In another studies by Maclean (1991), Chen and Chiew (2004), Singha et al. (2012) and Cao and Chiew (2014) found that the streamwise velocity increases near the bed because of suction resulting in the formation of a more uniform velocity distribution.

Previous studies neglected the downward seepage parameter which plays an important role in influencing the flow characteristic in a conveyance channel. This study therefore addresses how the turbulence characteristics in flows respond to a vegetated channel where downward seepage occurs. Consequently, a clear knowledge about the hydrodynamics over vegetation is required for appropriate and safe hydraulic designs. The main objective of this study is to investigate the effects of downward seepage on the flow structure in a channel covered with submerged flexible vegetation at a specific location for upstream, centre and downstream vegetation section. It provides important results relating to the turbulence characteristics, such as time-averaged velocity, Reynolds shear stress, turbulent intensities and third order moments. Analysis of the present experimental data allows understanding the change in the mean flow and turbulence characteristics because of the application of downward seepage in a vegetated channel.

2. Experimentation

Experiments were conducted in a glass-sided tilting flume with vegetation simulated by flexible cylindrical rods. The cross-section of the flume was rectangular, 17.24 m long flume, 1 m wide and a total depth of 0.72 m (see Fig. 1). The flume had a seepage chamber of 1 m wide and 0.22 m deep (out of total depth 0.72 m), located at 1.6 m from the upstream end of the flume, which collects water and allows free passage of water through the sand bed. The flow in the flume was driven by three 10HP centrifugal pump. The bed slope (S) was fixed at 0.15%. The discharge in the flume was measured with the help of a rectangular notch located at the downstream of the flume. Two Electromagnetic flow-metres (accuracy of $\pm 0.5\%$) were used for applying desired percentage of seepage discharge. The flow depth in the channel was measured with the help of a digital point gauge attached to a moving trolley which is a direct indicating gauge which eliminates observation errors because of vernier and scale reading. It could be set to zero anywhere in the operating range to permit easy relative level checking. The liquid crystal display was easy to read and had a resolution of 0.01 mm. The Acoustic Doppler Velocimeter (ADV), Vectrino®, was used to measure the velocity time series. ADV works with an acoustic frequency of 10 MHz and had a precision of ± 0.1 mm. Further, as far as the flow three-dimensionality is concerned, owing to the fact that the aspect ratios (that is the ratio of flume width to flow depth) were greater than 6, the flows in all the experiments were free from any three-dimensional effect induced by the side-walls (Yang et al., 2004).

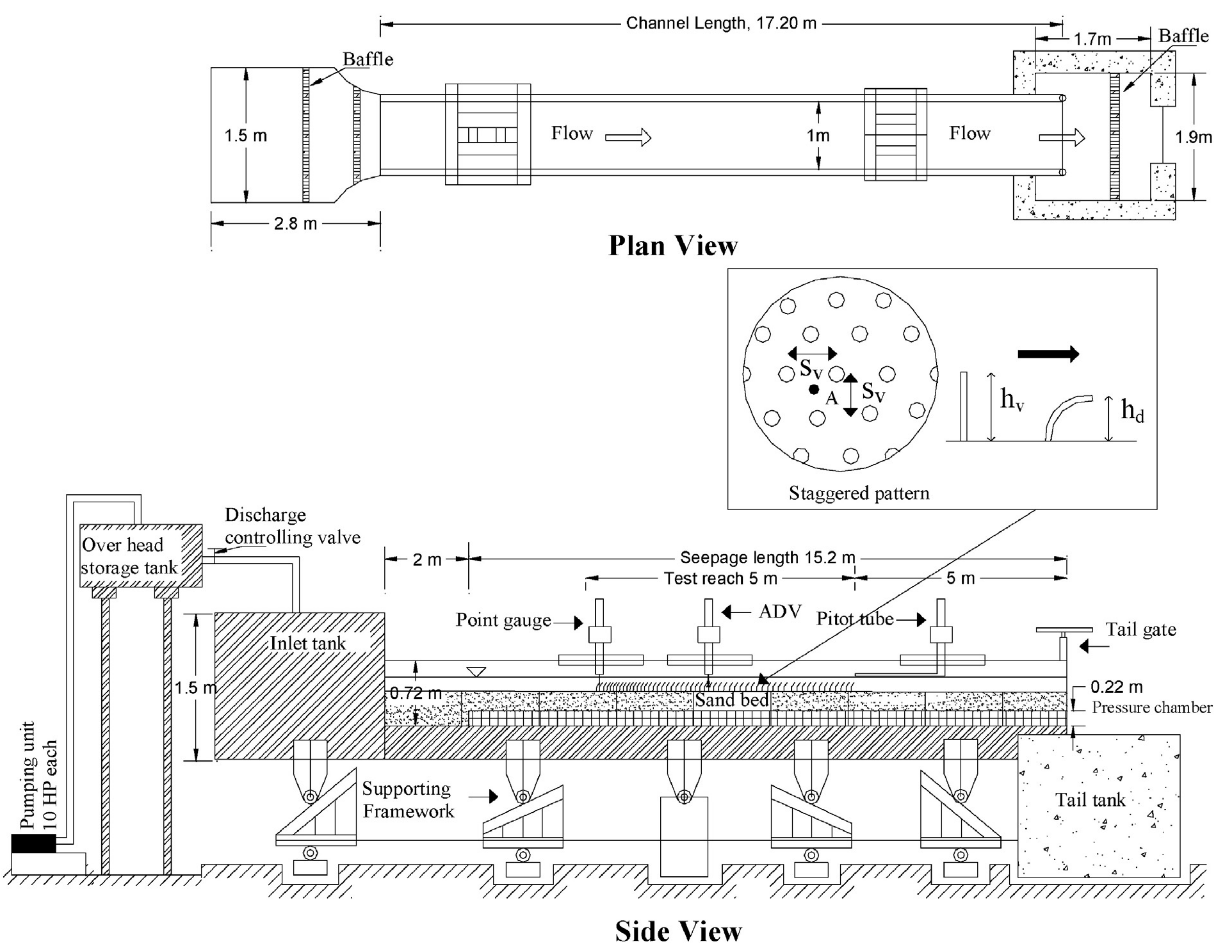

Fig. 1. Schematic diagram of the experimental flume set-up and the arrangement of vegetation and measurement location.