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Research papers

Partially obstructed channel: Contraction ratio effect on the flow hydrodynamic structure and prediction of the transversal mean velocity profile

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ABSTRACT

In this manuscript, we focus on the study of flow structures in a channel partially obstructed by arrays of vertical, rigid, emergent, vegetation/cylinders. Special attention is given to understand the effect of the contraction ratio, defined as the ratio of the obstructed area width to the width of the unobstructed area, on the flow hydrodynamic structures and to analyze the transversal flow velocity profile at the obstructed-unobstructed interface. A large data set of transversal mean flow velocity profiles and turbulence characteristics is reported from experiments carried out in a laboratory flume. The flow velocities and turbulence intensities have been measured with a 3D Acoustic Doppler Velocimeter (ADV)-Vectrino manufactured by Nortek. It was observed that the arrays of emergent vegetation/cylinders strongly affect the flow structures, forming a shear layer immediately next to the obstructed-unobstructed interface, followed by an adjacent free-stream region of full velocity flow.

The experimental results show that the contraction ratio significantly affects the flow hydrodynamic structure. Adaptation of the Prandtl's log-law modified by Nikuradse led to the determination of a characteristic hydrodynamic roughness height to define the array resistance to the flow. Moreover, an improved modified log-law predicting the representative transversal profile of the mean flow velocity, at the obstructed-unobstructed interface, is proposed. The benefit of this modified log-law is its easier practical applicability, i.e., it avoids the measurements of some sensitive turbulence parameters, in addition, the flow hydrodynamic variables forming it are predictable, using the initial hydraulic conditions.

1. Introduction

Aquatic plants/macrophytes usually play a number of roles on the hydrodynamic behavior and environment dynamic equilibrium of rivers and estuaries, i.e., turbulence, mixing and resistance to the flow (Righetti and Armanini, 2002), flood control, streambed and bank/shoreline stability, water purification, transport and dispersion of nutrients and tracers, protecting and restoring aquatic habitats. Natural vegetation in river floodplains and adjacent wetlands is characterized by multiple aspects (e.g., submerged/emerged, rigid/flexible, leafed/leafless, have branches/rods, high/low density) and can occupy the entire width or a portion of a waterway, reflecting a number of complex phenomena. Therefore, a good knowledge of the physical interaction between a flowing fluid and aquatic vegetation is required to promote best environmental management practice.

Two types of vegetation are usually defined (Järvelä, 2005): stiff/rigid (typically woody or arborescent plants) and flexible (herbaceous plants). Rigid arborescent plants, of random or regular arrays, are widely used as a way of protecting and managing of floodplains and banks (see Fig. 1). Tree farms are also considered as a partially porous obstruction, where fields of trees can be arranged in regular square rows. In addition, flow through rigid and emergent cylinder arrays is commonly found in several engineering application such as offshore structures, transmission lines, chimneys and array of silos. Several of these structures may also show geometries similar to the model geometry investigated in this manuscript. In the present study, we focus on the understanding of the various hydrodynamic phenomena occurring in the interaction between a flowing fluid and these structures.

A number of studies have been carried out towards gaining a better understanding of flow hydrodynamic structure in floodplains and wetlands. Many of these studies were focused on

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Nomenclature

a	total frontal area (area exposed to the flow) per unit array (m^{-1})
B	channel width (m)
b	width of the unobstructed area (m)
b_o	width of the obstructed area (m)
C_D	drag coefficient (–)
C_r	contraction ratio (–)
d	cylinder diameter (m)
g	gravity acceleration ($m\,s^{-2}$)
H	flow depth (m)
h	cylinder height (m)
k_s	hydrodynamic roughness height (m)
N	number of velocity sampling (–)
n	density of cylinders (cylinders m^{-2})
Q	channel discharge ($m^3\,s^{-1}$)
Re_0	inlet Reynolds number (–)
Re_2	free-stream Reynolds number (–)
s, s_x, s_y	space between cylinders (m)
T	water temperature (°C)
t	time (s)
U, V	streamwise and spanwise time-averaged velocity ($m\,s^{-1}$)
U_m	streamwise velocity at y_m ($m\,s^{-1}$)
U_0	mean channel velocity upstream of the cylinder arrays ($m\,s^{-1}$)
U_1	flow velocity inside the obstructed region ($m\,s^{-1}$)
U_2	free-stream velocity in the unobstructed area ($m\,s^{-1}$)
U^+, U^{++}	dimensionless streamwise velocities (–)
u^*	friction velocity ($m\,s^{-1}$)
u', v'	longitudinal and transversal velocity fluctuations (ms^{-1})
U'	u'-root mean square ($m\,s^{-1}$)
$U'V'$	spanwise Reynolds stress ($m^2\,s^{-2}$)
x, y, z	longitudinal, transversal and vertical coordinates, respectively (m)
x_{eq}	equilibrium velocity length (m)
y_m	effective shear layer origin (m)
y^+, y^{++}	dimensionless transversal coordinates (–)
α	empirical coefficient (–)
β	empirical constants (–)
δ_2	shear layer width (m)
Φ, C	integration constant (–)
φ	volume solid fraction of the cylinders (–)
κ	von karman's constant (–)
ν	Fluid kinematic viscosity ($m^2\,s^{-1}$)

Fig. 1. Example of floodplains with random and regular arrays of rigid trees.

velocity profiles and turbulent characteristics of partly emergent-vegetated channels (Naot et al., 1996; Nezu and Onitsuka, 2001; Xiaohui and Li, 2002; Helmiö, 2004; White and Nepf, 2007, 2008; Chen et al., 2010; Huai et al., 2011; Ben Meftah et al., 2014; Lima and Izumi, 2014; Wang et al., 2014). Most of these studies are based on laboratory experiments with different artificial roughness (in uniform flow). Experimental results show that the presence of the cylinders/vegetation arrays strongly affects the flow velocity distribution, forming a transversal sharp transition region at the interface between the obstructed and the unobstructed domains. Lima and Izumi (2014) indicated that the presence of partial vegetation/cylinders arrays produces velocity inflection and transverse shear, resulting in a Kelvin-Helmholtz instability with large-scale horizontal vortices centered around the edge of the vegetated area. These vortices have a strong influence on the velocity distribution and enhance the lateral exchange of mass and momentum between the vegetated zone and the open channel (Yang et al., 2015).

White and Nepf (2007, 2008) carried out detailed 2D flow velocity measurements with a Laser Doppler Velocimeter (LDV) in a 1.2 m wide, 13 m long flume, partially obstructed with a 0.4 m wide array of wooden, emergent, circular cylinders of three different volume densities ($\varphi = \pi ad/4 = 0.02$, 0.045 and 0.10), where a is the total frontal area per unit array and d is the cylinder diameter. The authors observed that at the interface between the obstructed and the unobstructed domains, a shear layer is found, possessing two distinct length scales: (i) an inner-layer thickness set by the array resistance, (ii) a wider outer region, which resembles a boundary layer, has a width set by the water depth and bottom friction (see also Ben Meftah et al., 2014). The authors argued that the interfacial Reynolds shear stress approximately balances the array resistance in the sharp transition region across the interface. While, in the boundary layer outside the array, the shear stress approximately balances the pressure gradient from the free-surface slope. According to the authors, as the flow develops the peak of the Reynolds stress shifts toward the interface and becomes more pronounced.

The free shear layer, formed at the interface, is subjected to transversal motion and may be shifted (increase of its width) away from the geometrical edge of the obstructed area (Naot et al., 1996; Ben Meftah et al., 2014). The longitudinal vorticity source, which is attenuated within the obstructed domain, increases externally