HYDRODYNAMIC FLOW STRUCTURES AT AN OBSTRUCTED-UNOBSTRUCTED INTERFACE IN A PARTIALLY VEGETATED CHANNEL

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KEY POINTS

- *In this manuscript we focus on the study of flow structures in a channel partially obstructed by an array of equi-spaced, vertical, rigid, emergent, circular steel cylinders*
- *Emergent vegetation strongly affects the flow hydrodynamic structures, forming a transversal abrupt velocity-transition region at the interface between the obstructed and the unobstructed domains*
- *A modified log-law predicting the representative transversal profile of the mean flow velocity at the obstructed-unobstructed interface is proposed and validated*

1 INTRODUCTION

Aquatic plants/macrophytes usually play a number of roles in the environment dynamic equilibrium, i.e., water purification, transport and dispersion of nutrients and tracers, providing habitat for wildlife, flood control, transfer of oxygen, carbon sink and streambed and bank/shoreline stability. The aquatic vegetation in a natural environment 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 an aquatic vegetation is required to promote best environmental management practice.

At the obstructed-unobstructed interface in an open channel flow partially obstructed by an array of cylinders/vegetation, the transfer of momentum takes the form of an apparent shear stress (*Naot et al.*, 1996; *White & Nepf*, 2007; *Ben Meftah et al.*, 2014; *Ben Meftah & Mossa*, 2015). *White & Nepf* (2007, 2008) carried out detailed 2D flow velocity measurements using 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. 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. Moreover, they observed that this peak in the equilibrium Reynolds stress profile coincides with the velocity inflection point, which is within 1-2 cm of the array edge and it is a point of high energy production.

White & Nepf (2007, 2008) assumed that the shear layer is unaffected by the vegetation/cylinders array, which is not always valid. 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 (e.g., *Naot et al.*, 1996; *Ben Meftah et al.*, 2014; *Ben Meftah & Mossa*, 2015). The longitudinal vorticity source, which is attenuated within the obstructed domain, increases externally leading to an overall increase of the effects of the secondary velocities (*Naot et al.*, 1996). In the unobstructed flow region, flow features resemble those of the boundary layer, whereas in the obstructed region the flow has the features of “porous obstructions” (*Huai et al.*, 2011; *Ben Meftah et al.*, 2014).

This paper summarizes how an emergent, vertical, rigid aquatic plants, which partially obstruct a channel cross flow (Figure 1), can influence the flow hydrodynamic structures. The similarity in feature of the flow distribution as a boundary layer has led to adapting the universal law of the wall, modified by *Nikuradse* (1933) as presented in eq. (1), to describe the transversal profile of the mean flow velocity.

$$\frac{U}{u^*} = \frac{1}{\kappa} ln\left(\frac{y - y_m}{k_s}\right) + C \tag{1}$$

where U is the local time-averaged velocity, u^* is the friction velocity, κ is the Von Karman's constant, y is the transversal coordinate, y_m is defined as a zero plane displacement of the logarithmic profile, k_s is an equivalent sand roughness and C is the integration constant.

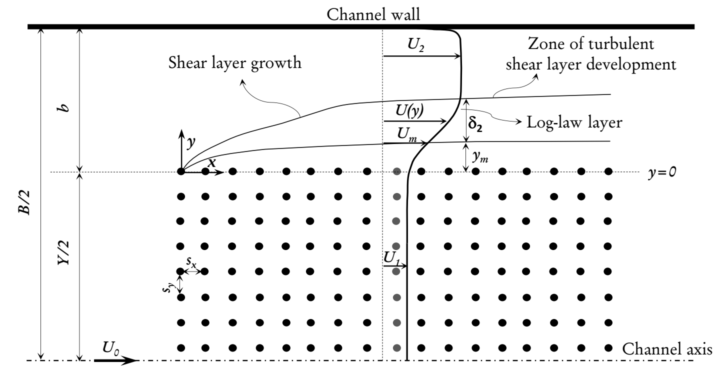

Figure 1. Problem description at the interface between the obstructed and the unobstructed domains. Note: B is the channel width, U_m is the flow velocity at y_m, U_0 is the inlet mean channel velocity upstream of the vegetation canopy, U_1 is the velocity inside the canopy region (defined as a time and spatially average pore velocity) and U_2 is the maximum velocity (almost constant) in the unobstructed domain. δ_2 is the shear layer width, defined as the distance between the transversal position at y_m and the position where $U(y)$ is equal to $0.99U_2$.

The experimental runs were carried out in a smooth horizontal rectangular channel at the Coastal Engineering Laboratory (L.I.C.) of the Department of Civil, Environmental, Building Engineering and Chemistry at the Technical University of Bari, Italy. The channel consisted of a base and lateral walls made of glass. The channel is 15m long, 4m large and 0.4m deep. Additional details concerning the channel setup can be found elsewhere in *Ben Meftah et al.* (2007, 2008) and *Ben Meftah et al.* (2010).

The model array was constructed of vertical, rigid, circular and threaded steel cylinders. Cylinders were arranged regularly and spaced longitudinally, s_x, and transversally, s_y, as $s_x = s_y = 5.0$cm, giving a density, n, of 400 cylinders/m^2. The flow velocity components were accurately measured using a 3D Acoustic Doppler Velocimeter (ADV); Vectrino manufactured by Nortek.

In this study, special attention is given to understand the effect of the obstructed width ratio (contraction ratio), defined as the ratio of the obstructed area width to the width of the unobstructed area, $C_r = (Y/2)/b$, on the flow structures, where Y is the full width of the obstructed area and b is the width of the unobstructed area (open area). A large series of experiments was carried out with four different values of C_r. The initial experimental conditions and some parameters of the investigated runs are illustrated in Table 1. Herein H is the flow depth, $Re_0 = U_0H/\nu$ is the inlet Reynolds number, $Re_2 = U_2H/\nu$ is the Reynolds number in the unobstructed area and ν is the kinematic water viscosity.

The transversal profiles of the measured flow mean velocity clearly show the development of a shear layer at the interface between the obstructed and the unobstructed flow areas. The experimental results indicate a strong effect of the width ratio C_r and the Reynolds number Re_2 on the flow hydrodynamic structures, i.e., the width of the shear layer δ_2, the characteristic hydrodynamic roughness height k_s, the zero plane displacement y_m, the flow velocities U_2 and U_m. Data analysis shows a negligible effect of the Reynolds number Re_0 compared to C_r- and Re_2-effects (Figure 2). In the present study, it was observed that, after determining y_m (determined experimentally based on the linearity of the measured streamwise velocity profile in semi-logarithmic coordinates) the von Karman coefficient associated with the measured velocity profiles (eq. 1) is significantly diffrent than the standard values (0.4) reported for flows over smooth and rough walls. In order to make all the profiles collapse into a single curve, Eq. (1) can be written as.

$$\frac{U}{u^*} = \frac{\alpha}{\kappa} ln\left(\frac{y - y_m}{k_s}\right) + C \tag{2}$$

Runs	C_r (-)	H (cm)	U_0 (cm/s)	y_m (cm)	U_m (cm/s)	δ_2 (cm)	U_2 (cm/s)	Re_0 (-)	Re_2 (-)	u^* (cm/s)	K_s (cm/s)
R0	3.21	28	8.93	1.87	8.567	28.02	18.17	20313	41341	1.30	7.56
R1	3.21	25	10.00	2.9	7.12	22.59	21.79	25000	54482	1.18	5.13
R2	3.21	22	11.36	2.4	9.04	25.50	24.81	18125	39567	1.34	4.87
R3	3.21	18	13.89	2.47	11.08	25.49	30.94	21250	47334	1.34	3.91
R4	3.21	14	17.86	1.89	14.74	24.81	38.53	21875	47193	1.46	2.98
R5	3.21	12	20.83	2.48	15.60	24.43	43.05	20625	42622	1.60	3.47
R6	1.05	28	8.93	3.14	4.79	44.65	15.29	20313	34773	1.00	10.21
R7	1.05	25	10.00	4.11	5.73	39.49	16.79	20188	33890	0.95	8.69
R8	1.05	22	11.36	4.5	6.71	35.35	18.94	20250	33747	0.95	7.42
R9	1.05	18	13.89	4.6	8.39	36.70	23.46	20375	34414	0.89	5.79
R10	1.05	14	17.86	3.79	11.01	34.95	30.98	20625	35784	0.89	4.25
R11	0.36	14	17.86	7.01	9.94	32.10	26.65	20813	31055	1.55	10.10
R12	0.36	12	20.83	6.83	11.73	32.91	31.95	21500	32970	1.61	8.64
R13	0.36	18	13.89	6.02	7.13	43.63	19.79	21125	30097	1.18	10.34
R14	0.36	22	11.36	5.82	5.66	35.98	15.52	21375	29197	1.05	12.15
R15	0.36	25	10.00	4.85	4.55	44.09	13.47	21563	29050	1.10	17.77
R16	0.16	25	10.00	2.35	3.79	36.76	11.85	20375	24152	1.38	33.66
R17	0.16	18	13.89	3.14	6.06	34.49	18.32	20813	27449	1.84	21.31
R18	0.16	12	20.83	3.99	10.09	26.94	29.22	21250	29803	2.24	10.67
R19	0.16	28	8.93	2.45	3.84	40.98	11.06	21563	26706	1.30	38.05

Table 1. Initial experimental conditions and some parameters of the investigated runs.

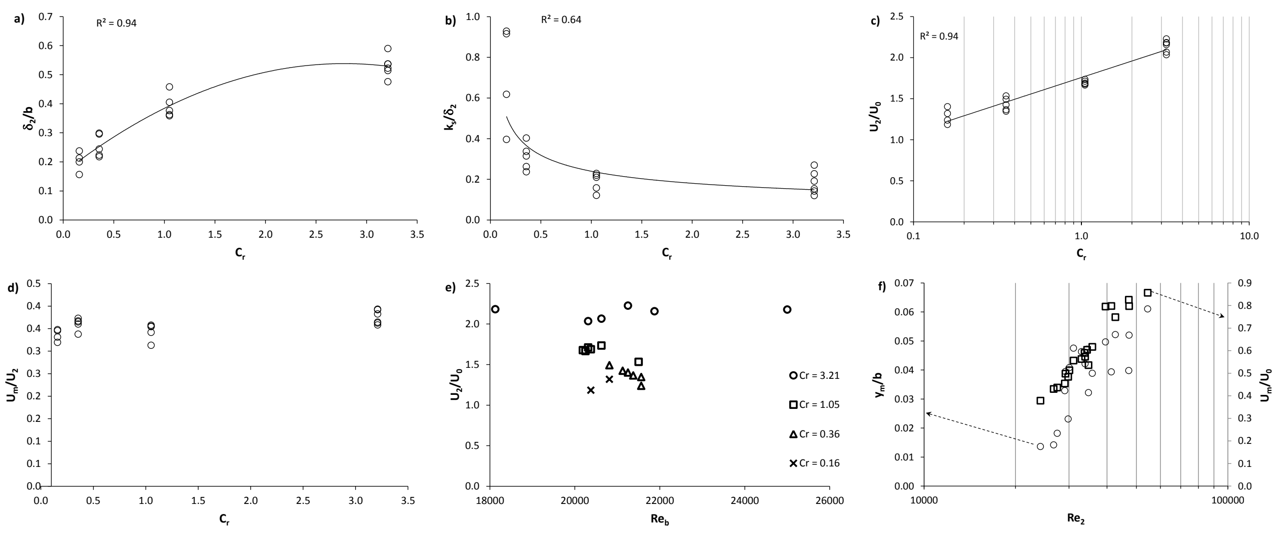

Figure 2. Effect of C_r on the flow structure, a) on of the shear layer δ_2, b) on the characteristic hydraulic roughness parameter k_s, c) and d) on the flow velocities U_2 and U_m, e) effect of Re_0 and f) effect of Re_2.

where α is a coefficient to be determined experimentally. Figures 3 a) and b) illustrate the trend of α as a function of $(U_2\text{-}U_m)/u^*$ and the U^+ as function of $(y^+)^{\alpha}$, respectively, where $U^+=U/u^*$ and $y^+=(y\text{-}y_m)/k_s$. Finally, a series of empirical equations to predict the different flow parameters is proposed:

$\frac{\delta_2}{b} = 0.241C_r^2 + 0.27C_r + 0.167$	(3)	$\frac{U_m}{U_2} \approx 0.35$	(6)
$\frac{k_s}{\delta_2} = 0.24C_r^{0.41}$	(4)	$\frac{y_m}{b} = 0.047ln\left(Re_2\right) - 0.452$	(7)
$\frac{U_2}{U_0} = 0.289ln\, C_r + 1.758$	(5)	$\alpha = 0.23\left(\frac{U_2 - U_m}{u^*}\right)$	(8)

Table 2. Empirical equations to predict the different flow parameters.

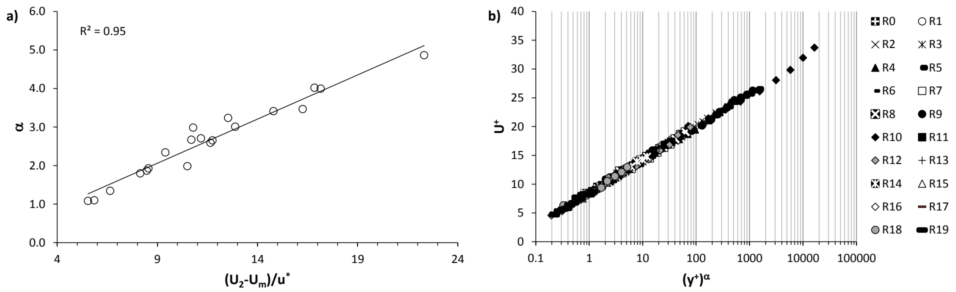

Figure 2. Modified log-law of the transversal profiles of the mean flow velocity, a) α trend as a function of $(U_2\text{-}U_m)/u^*$, b) plot of eq.(2).

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