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A simplified experimental method to evaluate equivalent roughness of vegetated river beds

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Abstract: In this paper a new method to experimentally evaluate roughness of vegetated river beds is proposed. Unlike the usual method of attaining uniform flow, the new method is based on measurements performed in boundary layer flows, conditions that in flow experiments with plants can be attained easier then in uniform flows. The described method can be applied either in case of smooth or vegetated walls. The friction factor f and Manning's n values so obtained are in agreement with literature results.

Keywords: flow resistance; uniform flow; boundary layer; vegetated river beds.

1. INTRODUCTION

In the past, vegetation on river beds was considered an unwanted source of flow resistance, and for this reason vegetation was commonly removed to improve the water conveyance.

Nowadays, vegetation is regarded as a means for providing stabilization for banks and channels, habitat and food for animals, and pleasing landscapes for recreational use. Therefore the preservation of vegetation is of great relevance for the ecology of water systems.

For this reason, the study of the effects of vegetation on the hydrodynamics of rivers represents one of the most important topics studied by hydraulic engineers today. Characteristics of flows over vegetated surfaces have been deepened with either experimental or numerical methods. Numerous studies have been carried out to examine the flow resistance of the streams on a vegetated bottom, and the main hydrodynamic characteristics of these streams, as the mean flow, the turbulent structures, and sediment transport (Lopez & Garcia 2001, Nezu & Onitsura, 2002, Tsuijimoto 1999, Tsuijimoto & Kitamura, 1990).

2. AIM OF THE PAPER

In a water current, vegetation may be regarded as a kind of bottom roughness that produces a resistance against the flow (Bettess 2003, Kouwen et al. 1969, Kouwen & Unny, 1973, Kouwen & Unny, 1981, Lopez and Garcia, 1997, Stone & Shen, 2002).

The main procedure to experimentally obtain the resistance characteristics of a bottom is to use a very long channel and generate within it a uniform flow. Therefore, long experimental laboratory channels must be realized in order to evaluate resistance characteristics of vegetated river bottoms.

Motivated by this observation, and by authors' experience of boundary layer flow over vegetated beds (De Felice and Gualtieri 2005, Gualtieri and Pulci Doria 2008), a simplified method is proposed that enables determination of the resistance coefficient by investigation of the boundary layer velocity profile. As the channel length necessary to produce a boundary layer is shorter, therefore, shorter laboratory channels are needed, and therefore this method allows easier determination of the resistance coefficient in a uniform flow.

Therefore, in this paper an experimental modelling of a particular kind of bottom roughness is described and a simplified method to evaluate the resistance coefficient is proposed.

3. GENERALITIES ABOUT RESISTANCE FORMULAS AND COEFFICIENTS

In a recent review (Yen, 2002) it is observed that each resistance coefficient can be considered either as cross section coefficient or as reach one, and that the usual resistance formulas can be considered as reach formulas to apply to uniform flows. It is possible to apply them also to not uniform flows, although to a very short reach, practically to a single cross section: therefore, in this case, the resistance coefficient can vary in the subsequent cross sections of the flow.

Referring to the reach formulas, the most frequently used, relating open-channel flow velocity V to resistance coefficients, are the Darcy-Weisbach, Manning and Chézy ones:

$$V=\sqrt{\frac{8g}{f}}\sqrt{RS}\,; \qquad V=\frac{1}{n}R^{2/3}S^{1/2}\,; \qquad V = C\sqrt{RS} \tag{1}$$

where f, n, and C are the Weisbach, Manning and Chézy resistance coefficients, and R = hydraulic radius, S = slope, g = gravitational acceleration. In case of cross section formulas, the slope S must be substituted by the head slope **J.** Comparing these formulas, it is possible to obtain the following expressions:

$$\sqrt{\frac{f}{8}}=\frac{n\sqrt{g}}{R^{1/6}}=\frac{\sqrt{g}}{C} \tag{2}$$

Among these resistance formulas, the authors choose the Darcy-Weisbach approach, because it is the most suitable for an exact evaluation of the flow resistances. Within this approach, the resistance coefficient f is related to the equivalent wall surface roughness, that here will be called ε, through the Colebrook-White formula:

$$\frac{1}{\sqrt{f}}=-K\,log\left(\frac{\varepsilon/4R}{a}+\frac{b}{Re\sqrt{f}}\right) \tag{3}$$

with Re Reynolds number defined as Re = 4VR/ν, and ν kinematic viscosity of the fluid.

The values of the constants a and b have been the object of many experimental surveys. In particular, in (Yen 2002) values for a and b, obtained by other researchers either for open channels with different aspect ratios or for wide open channels, are suggested. In Moody-type diagram, relative to circular full pipes, the values K = 2, a = 3.71 and b = 2.51 are used.

According to Marchi (1961) it is always possible to use the values of Moody-type diagram relative to circular full pipes also for open channels flows. This requires adoption of a suitable shape parameter ψ depending on the aspect ratio, so that the Colebrook-White formula becomes:

$$\frac{1}{\sqrt{f}}=-2\,log\,\frac{1}{\psi}\left(\frac{\varepsilon/4R}{3.71}+\frac{2.51}{Re\sqrt{f}}\right) \tag{4}$$

In particular, ψ assumes the value 0.83 for wide rectangular channels. The values of f so obtained are very similar to those suggested by Yen for wide channels.

4. PREVIOUS AUTHORS EXPERIMENTS ON BOUNDARY LAYER FLOWS

The elaborations performed in this paper are based on experimental data described in (De Felice and Gualtieri 2005, Gualtieri and Pulci Doria 2008).

The experiments were carried out in the plant sketched in figure 1. The main device was a channel 4m long and 15cm (b) wide, with variable slope, with plexiglas walls and bottom, coming out from a feeding tank supplied by a circulation pump, which took water from the drain tank downstream. The tank fed the channel through a rectangular adjustable sluice gate.

In the first sections of the channel, a zero piezometric head gradient boundary layer with horizontal free surface stream was generated. The boundary layer thickness increased in the subsequent sections along the channel, till it reached the same value as the height of the circulating flow, at a distance, from the inlet of the channel, depending on the dynamic characteristics of the flow itself (generally at least 50 cm).

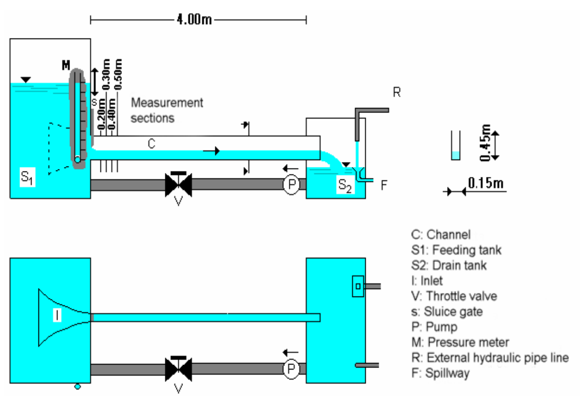

Figure 1. Scheme of the experimental plant.

Measurements were performed either with a smooth or a vegetated bottom. In particular, the vegetation was modelled by means of brass 4mm diameter cylinders with three different heights (5mm, 10mm, 15mm) placed according to two different regular geometries (respectively, a rectangular mesh 5*2.5cm^2 and a square mesh 2.5*2.5cm^2), pointed out synthetically as single and double density. Consequently, the projected area of vegetation per unit volume of water in the flow direction (Tsujimoto *et al.*, 1992) were, respectively, 3.2m^{-1} and 6.4m^{-1}. Combinations of three different heights and two different densities produced six different vegetated bottoms.

In all the seven considered flow conditions (smooth bottom and six different vegetated bottoms), the same experimental setting was considered. In particular, the height of the sluice gate was set at 7.49cm so that the height in the vena contracta was at 4.62cm; the load on the vena contracta was at 10.34cm, and the resultant velocity of the free-stream was at 1.424 m/s.

Moreover, it was necessary to ensure the zero value of piezometric head gradient of the boundary layer, in each one of the seven considered flow conditions. This corresponded to hold the free surface of the current horizontal, at least in the first 50cm where the boundary layer developed. Therefore, it was necessary to suitably incline the channel, taking into account the vegetation type, whose possible increase in height and density would generate a corresponding increase of head losses, which would need to be balanced by a suitable increase of channel slope. The chosen slopes' values are reported in both the subsequent tables 3 and 4. The test sections were set at 20, 30, 40 and 50 centimetres from the channel inlet. In each test section two measuring verticals were considered, differently positioned with respect to the cylinders. The first one was set at the centre of either a rectangular or a square mesh. The second one was set along a cylinder row and at the centre of the lateral