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Influence of Vegetation Height and Density on a Turbulent Boundary Layer

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Abstract

In last years vegetated surfaces problems are becoming more and more important in hydraulic research, whereas boundary layer problems are always a very important topic of fluid mechanics. In this paper the influence of submerged rigid vegetation on the development of a water equilibrium boundary layer in a rectangular channel is experimentally investigated. Vegetation is modelled through vertical cylinders inserted in the channel bottom: two different cylinders heights and two different cylinders densities have been considered, so that four different vegetation conditions have been investigated and always compared with the same boundary layer without vegetation. Local mean velocity distributions in four subsequent test sections have been measured through an LDA system. The main results obtained are the following ones: 1) vegetation presence increases boundary layer thickness; 2) with the investigated cylinders heights and densities the boundary layer behaves yet as an equilibrium one; 3) the equilibrium characteristics depend on either cylinders height or cylinders density; 4) it is possible to define an index which summarizes the aforementioned equilibrium characteristics.

Introduction

Vegetated surfaces problems

It is generally agreed that vegetation increases flow resistance, changes backwater profiles and modifies sediment transport and deposition. In the past vegetation along rivers and on floodplains was traditionally regarded a nuisance and for this reason it has been usually eliminated. At the present in river restoration and environmental engineering natural river characteristics are sought after, implying that the physical habitat and flow conditions should be as close as possible to a pristine reach.

Much of the earlier work on the hydraulic properties of riverine vegetation was conducted by agricultural engineers who concentrated on determining roughness coefficients or developing design methods, rather than on obtaining a better understanding of the physical processes. Conventional approaches typically use reference publications for selecting a roughness coefficient, which groups all sources of flow resistance, including vegetation, into Manning's n. Significant advances have been made to gain a better understanding of flow phenomena in floodplain and wetland flows. A considerable amount of research has been carried out in developing resistance laws for channels with rigid vegetation, flexible vegetation, and various combinations. Recently, several studies have focused on velocity profiles and turbulent characteristics of vegetated channels. Overall, an abundance of studies, however, is based on laboratory experiments with simple artificial roughness, whereas in fact natural vegetation exhibits a wide variety of forms and flexibility. In hydraulic analysis, non-submerged and submerged conditions are typically distinguished, and, in addition, two types of vegetation are usually defined: rigid (woody or arborescent plants) and flexible (herbaceous plants) [11, 12, 13, 15, 16].

Boundary layer problems

On the other side, the hydrodynamic behaviour of a boundary layer is one of the most important topics of fluid mechanics. The hydrodynamic laws which describe boundary layer behaviour are now reasonably well known. In particular, with regard to an air boundary layer, the non dimensional value of the pressure gradient along the flat plate is the most important parameter which controls the local mean velocity distributions along the direction orthogonal to the plate. In fact, if this parameter is kept constant along the plate, the boundary layer is called an "equilibrium boundary layer" and the non dimensional velocity distributions, represented as a velocity defect law, does not vary along the plate.

A more sophisticated type of boundary layer flow, much investigated in international literature [1, 8, 9, 10, 14], is the turbulent boundary layer under free stream turbulence.

Two of the authors worked in previous years on this research field [2, 3, 4, 5, 6], performing their experimental tests in a water channel. The investigated boundary layers were always equilibrium ones with zero-piezometric head gradient (condition that for water is equivalent to the zero- pressure gradient in air).

Aim of the paper

Authors are not acquainted of any presence, in the however growing scientific literature on vegetated streams, of the problem of vegetation effects on boundary layers.

In a recent paper [7] authors began to study how bottom vegetation can affect the development of a water boundary layer. In particular submerged rigid vegetation placed on the bottom of the channel was considered, and was modelled through groups of vertical cylinders, 4 mm diameter, placed in rectangular meshes 5.0*2.5 cm^2; each cylinder was 5 mm high in a first experimental condition and 10 mm high in a second experimental condition. A third experimental condition, without cylinders at all, was also obviously considered for comparison.

This paper is an advance of [7]. In particular either the investigated boundary layer flow or the heights of the cylinders modelling vegetation are the same ones as in [7], but the cylinders density has been increased: in fact they are placed in square meshes 2.5*2.5 cm^2.
The main purpose of this paper is to deepen, employing also the results of [7], the mixed influence on boundary layer development of cylinders heights and densities.

Experimental plant
The experimental plant represented in figure 1, carefully described in [7], has been used.

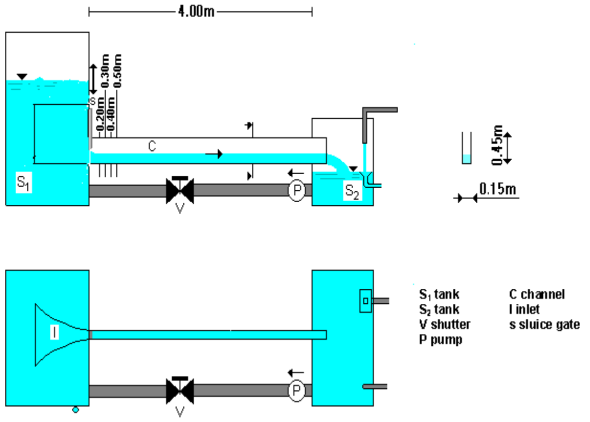

Figure 1. Experimental plant.

Its main device is a variable slope channel 4 m long and 15 cm wide, with plexiglas walls and bottom, coming out from a feeding tank supplied by a circulation pump. This tank feeds the channel through an adjustable rectangular sluice gate. The inlet towards the sluice gate is modelled through a suitable plexiglas device.
In the channel, until a distance of some decimetres from the sluice gate, a boundary layer flow is generated on the bottom. Moreover, due to feeding tank characteristics, this current showed, in every flow condition, a not at all negligible free stream turbulence.
The instantaneous velocity measurements and the local mean velocity values have been carried out through an LDA technique.

Vegetation modelling
As already said, vegetation was modelled through groups of vertical cylinders placed in square meshes 2.5*2.5 cm^2. *In particular, they have been arranged in the following way.* The longitudinal rows of cylinders were 2.5 cm far each another and 1.25 cm far from the lateral walls. The first cylinder of each row was placed 1,25 cm from the channel inlet (sluice gate section).
In this way, the whole arrangement was symmetric, the centreline of the channel bottom was free from cylinders and it was possible to carry out velocity distributions measurements on it. In particular the four test sections that have been chosen, likewise in [7], are at 20 cm, 30 cm, 40 cm, 50 cm respectively far from the channel inlet. These test sections were all placed exactly between two following rows, so that the measurement verticals lied exactly in the centre of each square mesh.

Experimental surveys carried out and relative results
In order to compare all experimental conditions some fundamental hydraulic parameters have been kept constant and equal to the corresponding ones in [7].
The height of the sluice gate was always of 7.49 cm, and the height of the vena contracta was of 4.61 cm.
The head of the tank above the vena contracta was always of 10.34 cm and the velocity in the vena contracta was of 1.424 m/s. The flow-rate was of 9.85 l/s.
As in [7], in each condition, in order to have always an equilibrium boundary layer with zero-piezometric head gradient in the flow direction, the free surface was kept horizontal.
Therefore it has been necessary to change the slope of the channel in each experimental condition, because of the different bottom friction head losses without cylinders, with 5 mm and 10 mm cylinders heights. In particular in the two conditions 1.15% and 2.05% slopes were established, which can be compared to the 0.25% characteristic of smooth bottom condition. In such a manner, the hydraulic head was kept constant and equal to 10.34 cm also along the whole current in each flow condition; and the velocity in the external layer was 1.424 m/s everywhere.
In each experimental condition, local mean velocity distributions have been measured in the four aforementioned test sections. Such experimental velocity distributions, together with the smooth bottom velocity distribution, have been represented in figures 2, 3, 4, 5.

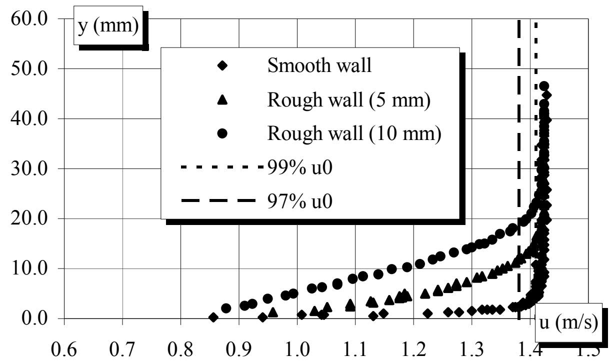

Figure 2. Velocity distributions in section 1 (20 cm from the inlet).

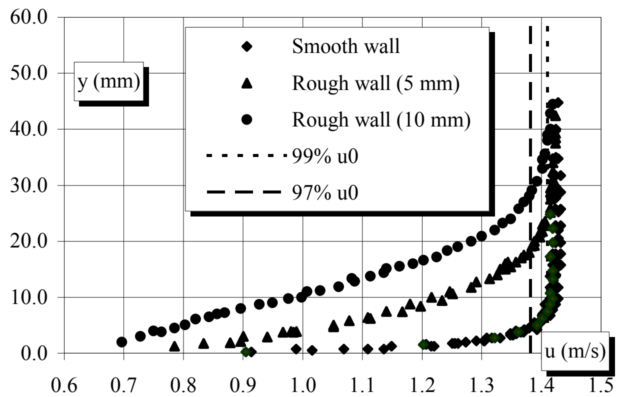

Figure 3. Velocity distributions in section 2 (30 cm from the inlet).

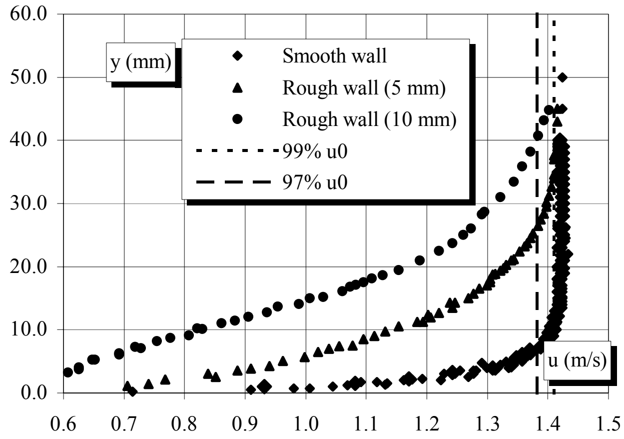

Figure 4. Velocity distributions in section 3 (40 cm from the inlet).

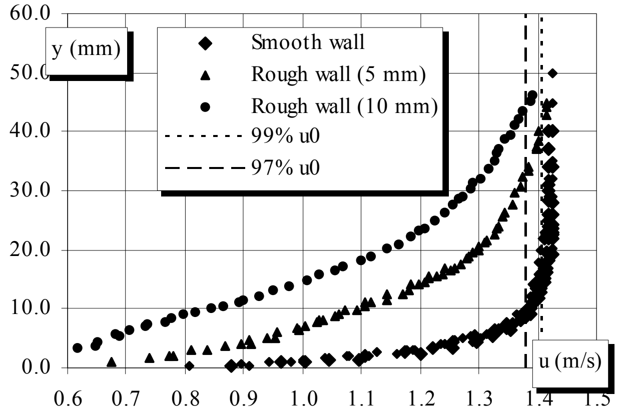

Figure 5. Velocity distributions in section 4 (50 cm from the inlet).

Some first qualitative results are immediately evident.
First of all, the vegetation presence affects widely velocity distributions in boundary layers. In particular, because of the presence of vegetation, the boundary layer thickness grow and the velocity inside the boundary layer decreases.
In particular, the values of the 99% boundary layer thickness (δ_{99}) in the four test sections (20 cm, 30 cm, 40 cm, 50 cm) are the following ones:
Smooth bottom: mm 3.8, 7.1, 10.9, 13.5.
5 mm cylinders height: mm 16.0, 26.3, 35.1, 44.0.
10 mm cylinders height: mm 22.0, 33.9, 47.7, 52.4.
These values have been evaluated through a special procedure fully described in [7], because it is difficult to read directly on the diagrams the δ_{99}.
A further qualitative result is that it is possible to notice that no evidence appears, at first sight, of possible irregularities of the velocity distributions at the cylinders height.
At a deeper insight, it would be possible to observe, in the section 20 cm far from the sluice gate, a little irregularity (an elbow) in velocity distributions. This phenomenon is clearly caused by the greater resistance met by the current in its lower part where the cylinders are present, and it is related in literature about uniform or steady vegetated currents [17]. Either in [7] or in this paper it is not very evident because of the fairly low adopted cylinders densities.
In any case the conditions that produce the irregularity in the case of boundary layer must be deepened through further experiments, which will be carried out in a next paper.

Non dimensional velocity distributions and equilibrium characteristics

All the twelve velocity distributions reported in figures 2, 3, 4, 5 can be transformed in non dimensional ones through the u_0 velocity in the external layer and the already obtained δ_{99} values. In figure 6 non dimensional velocity distributions in three experimental condition (smooth bottom, 5 mm and 10 mm cylinders height) are reported.
A simple look to the figure shows clearly that the distributions relative to the same experimental condition but to different test sections overlap one another (with the almost invisible exception of the irregular points of the 20 cm test section) so that only three different diagrams appear, every one relative to a different vegetation condition (smooth bottom, 5 mm and 10 mm cylinders height).
In figure 7, in order to have a fruitful comparison, the correspondent diagram that had been presented in [7] is represented. It refers always to smooth bottom, 5 mm cylinders and 10 mm cylinders height, but to a lower vegetation density value (rectangular meshes 5.0*2.5 cm^2 instead of square meshes 2.5*2.5 cm^2). Also in this diagram the distributions relative to the same experimental condition but to different test sections overlap one another.

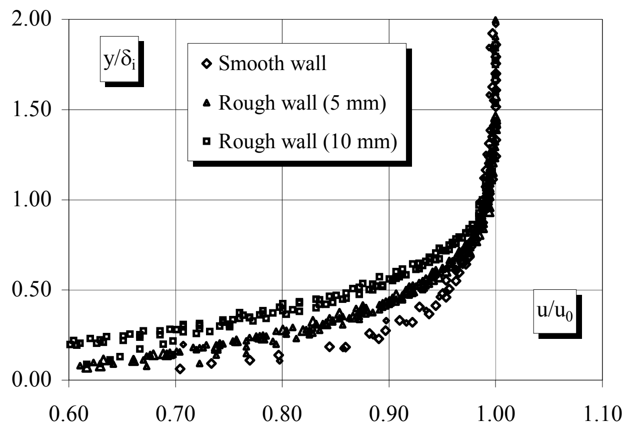

Figure 6. Non dimensional velocity distributions (square meshes).

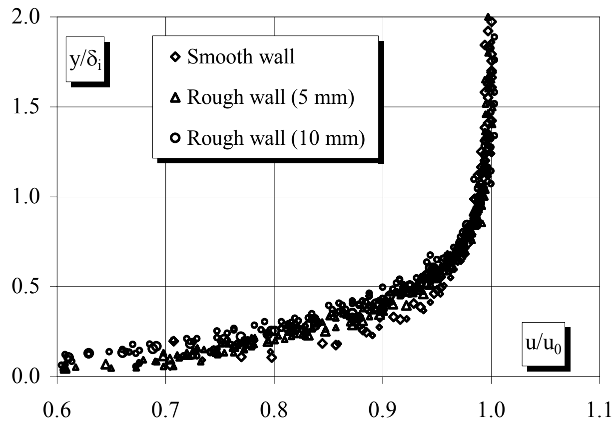

Figure 7. Non dimensional velocity distributions (rectangular meshes).

This behaviour represents the clear mark of the equilibrium state of the boundary layers in each experimental condition, not only in the case of smooth bottom, as it was obvious, but also in the cases of vegetated surfaces . This conclusion, as it

has been verified in [7], can be drawn also if the distributions are not represented in the theoretically requested shape of velocity defect laws. The circumstance that the boundary layers over vegetated surfaces appear to be equilibrium ones, at least in the considered conditions, is an intriguing result.
In conclusion, therefore, except the few considered exceptions which regard only the inner part of the boundary layer and only the first test section, the considered boundary layers appear to be equilibrium ones: namely in each experimental condition their velocity distributions in different test sections superimpose one another.

Difference of equilibrium conditions in different hydrodynamic current conditions

As already stressed, in both figures 6 and 7 it is clear that the three velocity distributions do not overlap. A direct comparison between the two figures shows that also distributions relative to the same cylinders height but different cylinders density do not overlap.
Therefore, in the considered experimental conditions, our pattern of vegetation does not produce the well known elbow in the velocity distributions, but, in any case, it influences the overall trend of the distributions themselves. This influence depends on cylinders either height or density.
It is even possible to define a simple shape index of the distributions, defined as the ratio δ_{99}/δ_{97} (with an obvious meaning of the symbols). This index is not based on displacement thickness and momentum thickness, as more typical in boundary layer literature, but has the advantage to be more immediately intelligible and measurable. The values of this shape index in the different experimental conditions are given in following table:

	0 mm	5 mm	10 mm
Zero density	1.65	1.65	1.65
Rect. mesh	1.65	1.50	1.40
Square mesh	1.65	1.38	1.25

Table 1. Table of the shape index

From this table, it is clear that this index varies with height and density of the cylinders: in particular it regularly decreases with cylinders either height or density.

Conclusions

In recent years much attention has been paid to the problem of the behaviour of free stream currents with vegetated surfaces in relation to atmospheric or river flow problems. The study of the influence of vegetated bottom on the growth of turbulent boundary layer can let us deepen some further currents behaviour characteristics.
From the point of view of basic fluid mechanics, the most important conclusion coming from the analysis of the experimental results is that, in case of regular submerged rigid cylinders-shaped vegetation, the boundary layer flow, if the free surface is kept constant and excluding some minor exceptions, behaves as an equilibrium boundary layer.
Moreover the equilibrium conditions are different in the boundary layer without cylinders, or with cylinders of different heights or densities. These different equilibrium conditions can be summarized by a very simple shape index which depends on vegetation characteristics.

Acknowledgements

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References

[1] Bandypadhyay, P.R. Reynolds Number Dependence of the Freestream Turbulence Effects on Turbulent Boundary the Layers *AIAA J.* **30(7),** 1992, 1910-1912.

[2] Gualtieri, P. & Pulci Doria, G. Non dimensional distribution of longitudinal integral length scales in a turbulent boundary layer *FLUCOME '97 Congress* Hayama, Japan, 1997, 161-166.

[3] Gualtieri, P. & Pulci Doria, G. A proposal of a physically based thickness definition and of a new mean velocities distribution law in a turbulent boundary-layer on the ground of LDA measurements *13th Australasian Fluid Mechanics Conference,* Melbourne, Australia, 1998, 845-848.

[4] Gualtieri, P. & Pulci Doria, G. 1999 Boundary Layer Intermittency Model *IUTAM Symposium on Geometry and Statistics of Turbulence,* Hayama, Japan, 1999, 379-384.

[5] Gualtieri, P. & Pulci Doria, G. 2001 A Correct Model of Variance, Skewness, Kurtosis in Boundary Layer with Turbulent External Layer *14th Australasian Fluid Mechanics Conference,* Melbourne, Australia, 2001, 259-262.

[6] Gualtieri, P. & Pulci Doria, G. 2003 A correct model of longitudinal integral length scales in boundary layer with turbulent external layer *2nd Int. Conf. on Heat Transfer, Fluid Mechanics, and Thermodynamics H.E.F.A.T.,* Victoria Falls, Zambia, 2003.

[7] Gualtieri P., Pulci Doria G. & Taglialatela L. Effect of vegetation on boundary layer with turbulent free stream layer *2nd Int. Conf. on Fluvial Hydraulics RiverFlow 2004,* Napoli, Italy, 2004, 381-388.

[8] Hancock, P.E. & Bradshaw, P. Influence of Free-Stream Turbulence on Turbulent Boundary Layers *J. Fluids Eng.* **105**, 1983, 284-289.

[9] Hancock, P.E. & Bradshaw, Turbulent structure of a boundary layer beneath a turbulent free stream *J. Fluid Mech.* **205**, 1989, 45-76.

[10] Hoffmann, J.A. & Mohammady, K. Velocity Profiles for Turbulent Boundary Layers Under Freestream Turbulence *J. Fluids Eng.* **113**, 1991, 399-404.

[11] Kouwen, N. & Unny, T.E. Flexible roughness in open channels *J. Hydraulic Eng.* **99(5)**, 1973, 684-698.

[12] Kouwen, N. & Unny, T.E. Flow resistance in vegetated waterways *Trans. ASEE* **24(3)**, 1981, 684-698.

[13] Kouwen, N., Unny, T.E. & Hill, H.M. Flow retardance in vegetated channels *J.Hydraulic Eng.* **95(2)**, 1969, 329-342.

[14] Meier, H.U. & Krepli, H.P. Influence of Freestream Turbulence on Boundary-Layer Development *AIAA .J.* **18**, 1980, 11-15.

[15] Nezu I. & Onitsuka Kouki Turbulent structures in partly vegetated open channels flows with LDA and PIV measurements *J. Hydraulic Research* **39(6)**, 2001, 629-642.

[16] Stone, B. M. & Shen, H. T. Hydraulic Resistance of Flow in Channels with Cylindrical Roughness *J. Hydraulic Eng.* **128(5)**, 2002, 500-506.

[17] Tsuijimoto, T., Shimuzu Y. & Okada T. Turbulent open-channel flow over bed covered by rigid vegetation *J. Hydroscience and Hydraulic Eng.* **10 (2)**, 1992, 13-25.