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# Experimental observations of flow field around macro-scale roughness

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## ABSTRACT

The turbulent flow in the case of macro-roughness elements is strongly affected by the vortex structures which develop around the macro-elements and force the flow to deviate from the undisturbed uniform flow, for which the logarithmic law of the wall is assumed to be valid. In this case macro-roughness element planimetric arrangement plays a fundamental role in energy dissipation behavior. Indeed it seems that an optimal macro-roughness element spacing value exists, able to maximize flow resistance. This special behavior may be related to the transition from an isolated-roughness to a wake-interference flow.

This paper presents the preliminary results of a laboratory study on the flow around macro-roughness elements according to different special arrangement in order to evaluate the wake interference: i) single test block and ii) one row of test blocks with five different values of the distance between two elements.

The velocity profiles are measured in order to reconstruct the flow field around the test block to the purpose of estimating the spatial evolution of a steady wake. The preliminary analysis of the results is here presented.

*Keywords: Flow resistance, wake interaction, turbulence.*

## 1 INTRODUCTION

The measurement of the flow drag force acting on individual bed material element gives an important contribution to the study of flow resistance and sediment transport in river channels.

Notwithstanding that macro-scale roughness elements frequently occur in mountain streams, the role played by their geometry on turbulent flow and flow resistance is not completely understood. As pointed out by Morris and Wiggert (1971), at least two main different conditions may occur at different planimetric concentration of the boulders:

- *Isolated-roughness*, when the elements are at relative 'high' distance and no wake interaction occurs. In such case flow resistance is proportional to the number of elements;
- *Wake-interference,* when the elements are sufficiently 'close' together and the wake behind each element overlaps with the next element. In such case flow resistance is no more given by the sum of the single effects, since the vortex generation and dissipation phenomena associated with each wake will interfere with those of the adjacent elements.

Several geometric parameters determine flow resistance in case of low relative submergences, such as macro-roughness element shape, dimension and orientation. Some studies (Rouse, 1965; Bathurst et al., 1981; Ferro and Giordano, 1993; Baiamonte et al., 1995) underline that especially macro-roughness spatial density and planimetric arrangement are involved in the dissipative mechanism occurring in macro-scale roughness streams.

Physically based alternative models (Bathurst et al. 1981; Colosimo et al., 1988; Baiamonte and Ferro, 1997) point to the need to incorporate details of the surface geometry (e.g., roughness concentration and arrangement) and the cross-sectional or channel geometry, in addition to the roughness height.

The role played by the spatial density of the roughness on turbulent flow has been also recently discussed by Lawrence (2000), in the case of overland flow: in particular, he pointed out that in the macro-roughness case the observed coefficient of drag per element is much higher than that for an isolated element, and a model based on element form drag alone underestimates the observed friction.

Finally the influence of macro-roughness planimetric concentration on flow resistance has been also pointed out by Canovaro et al. (2007), showing a non-monotonic behavior of dimensionless Chezy coefficient as a function of macro-roughness concentration. In particular it appears that when the concentration of the roughness is within an optimal range flow resistance is maximum. This special behavior may be related to the transition from an isolated-roughness to a wake-interference flow.

In the present paper experimental observations on turbulent flow around macro-roughness elements have been performed for a deeper understanding of the flow structures around a single element and of the wake interference in the case of 'close' elements. In the performed experiments the depth of flow *Y* is generally of the same order as the characteristic dimension *D* of the test block. As a result, the approaching flow is affected by the obstacle, with significant changes to the water surface. Here, the condition of low submergence is considered.

## 2 EXPERIMENTAL SET-UP

### 2.1 *Apparatus*

Experimental runs were conducted in a tilting recirculating flume which was 10 m long, 0.36 m wide and 0.4 m deep. The recirculating water discharge was regulated by a valve and measured by means of an electromagnetic flow-meter.

Regular test blocks (50×100×50 mm) were employed as macro-roughness elements, placing them over a granular bed in the 4 m long measuring reach, according to various arrangements and spatial density values. Two different patterns were employed for characterizing different values of the hydraulic resistance:

- *single block* experiment, in order to observe flow structure around a single element,
- *one row* experiment, in order to observe flow structure around elements displaced in single line along the flow direction (Figure 1).

The characteristic dimension of the test block is assumed to be the face length against the flow $D = 50$ mm; the block shape has been chosen because of the sharp edges in order to strengthen the wake effect.

The granular bed constituting the bottom of the measuring reach was made by granular material with uniform size *d* of 7 mm, glued on a 4 m long, 0.365 m wide and 10 mm thick PVC sheet. The measuring reach was located at about 5 m from the flume entrance section.

A 1.5 m long reach of quarry rubbles was positioned before the beginning and after the end of the measuring reach to avoid large-scale disturbance in the reach under investigation: all measurements were carried out in a region of fully developed flow.

Total water depth *Y* was measured by means of a set of 40 piezometers placed under the granular bed and connected to the main flow by means of holes drilled into the PVC sheet.

The vertical flow velocity profiles were measured with an acoustic Doppler profiler, which revealed the one-dimensional profile in the longitudinal direction. Each profile was characterized by a measurement duration of about 130-150 s and a sampling frequency of about 4300 Hz. The spatial resolution between two velocity points along the vertical profile is around 0.36 mm.

### 2.2 *Experimental activity*

The hydraulic conditions of the experimental runs are defined in terms of discharge *Q* and bed slope *S*.

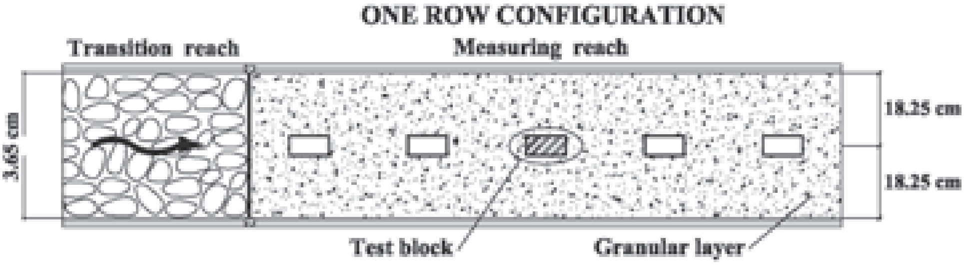

Figure 1. Sketch of the experimental configurations of the one row experiment.

In the present work we focus on the experiments carried out employing the *one row* configuration in the case of a flow discharge equal to 15 l/s and a channel slope 0.5%. Five different arrangements corresponding to a distance *d* between two elements equal to 5, 10, 15, 20 and 30 centimeters are taken into account. In order to compare such measures with a reference experiment, also the experimental run obtained in the *single block* case is presented.

Experiments have been carried out under the hypothesis of steady flow and spatially averaged uniform conditions.

For each experiment several flow velocity profiles have been measured. The planimetric sketch of the measurement points pertaining to the *one row* configuration in the case of *d* = 20 cm is presented in Figure 2: axes *x* and *y* respectively indicate the transversal and the longitudinal coordinates along the flow direction, whereas *z* is the vertical coordinate; the axis origin is placed at the granular bed altitude, at the test block center; axis orientation is given in Figure 2. The planimetric sketch of the measurements points in the case of different values of *d* is similar.

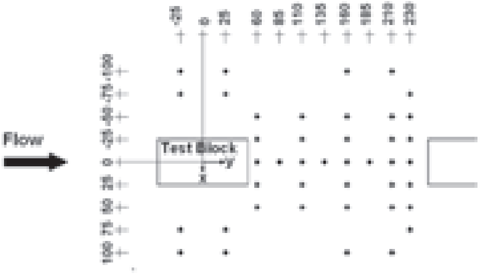

Figure 2. Planimetric sketch of the velocity profile measurement points in the case of *one row* configuration (*d* = 20 cm). Longitudinal and transversal coordinate are expressed in mm.

## 3 RESULTS AND DISCUSSION

The preliminary results herein presented regard experiments carried out at a discharge of 15 l/s and with a flume slope of 0.5 %.

The analysis of the *single block* run was preliminarily discussed by Canovaro and Francalanci (2007) and it is here recalled for the purpose of comparison with the *one row* experiments, that have the aim to take into account the influence of the distance *d* between two elements on the wake volume.

The velocity profiles measured in the one row configuration along the *y* axis are shown in Figure 3, for the case *d* = 20 cm. The longitudinal profiles along the flow direction show the effect of the macro-roughness elements on the flow itself: in the rear of the front block negative velocities occur, giving evidence of a recirculation zone which extends farther downstream. The inversion of the velocity profile is almost disappeared in the middle between the two blocks, while in the front of the rear block the flow is again slowing down and negative velocities appear. The inversion of the longitudinal velocity profiles can be observed in all the performed *one row* experiments; the distance between two elements seems to play a role on the expansion of the wake downstream of the front block, as it will be discussed later.

The vertical slices of longitudinal velocity contour lines in the flow region between two blocks, in the case of *d* = 10 cm, *d* = 20 cm and *d* = 30 cm, are shown in Figures 4-6: it can be observe that a flow region with negative velocities exists.

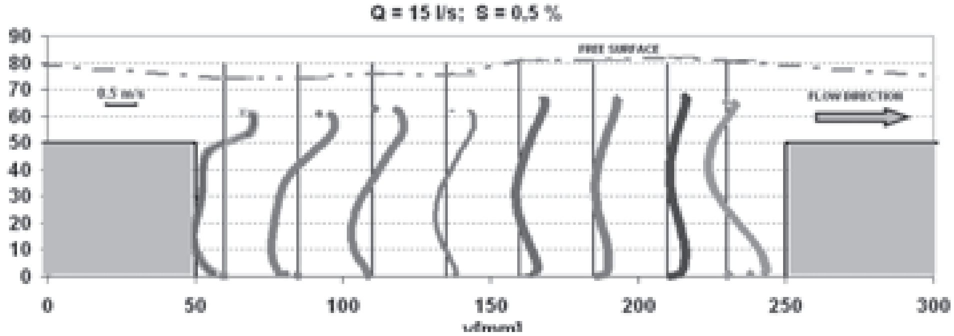

Figure 3. Velocity profiles along the y axis, (x = 0 mm), in the case of *d* = 20 cm

As a rough designation, in this preliminary analysis we consider that the wake region correspond to the negative velocities region. According to such hypothesis it appears that when distance *d* is 10 cm the wake occupies all the flow region enclosed between two consecutive blocks; in the case of *d* = 20 cm the wake inhabits a part of the flow region, whereas in the case of *d* = 30 cm the wake is present only in a little portion of the flow region and in the other part positive velocities occur. In all the cases presented here negative velocities occur also in the upper part of the flow in the front of the blocks.

The volume of the negative velocities region, that will be indicated as $V_{vn}$ in the following, can be estimated from the local values of the velocity field within the wake, and is shown to be related to the distance *d* between two elements (Figure 7).

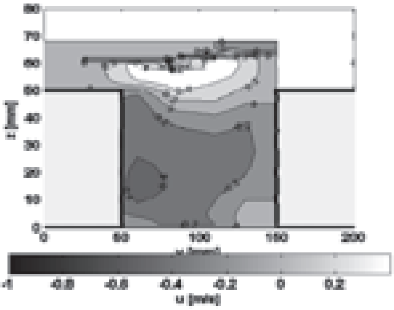

Figure 4. Vertical slice of a wake between 2 elements; d=10 cm.

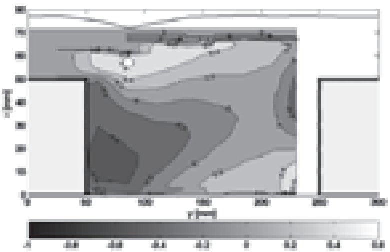

Figure 5. Vertical slice of a wake between 2 elements; d=20 cm.

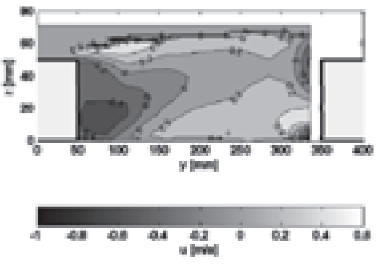

Figure 6. Vertical slice of a wake between 2 elements; d=30 cm.

It can be seen clearly that the volume of negative velocities, which is assumed to correspond to the wake volume, is slightly increasing with the distance between two elements in the row, and it is of the order of twice the length of the block.

Moreover, the same values of the volume of negative velocities $V_{vn}$ are shown together with the data of the single block experiment for comparison purpose, in Figure 8: the *single block* experiment does not correspond to any measured distance *d* between elements because it has a theorical infinite value in the 'isolate boulder' experiment, hence we assumed the distance *d* equal to the length of the flume.

The results show that when the flow is not confined among the macro-roughness elements the interference of the flow field with the obstacle propagates downstream and the wake turbulence is carried by the flow, while when several macro-roughness elements are located close to each other they indeed interact among themselves; the structure of the flow fields clearly revealed this interaction and the wake volume in terms of negative velocities is strongly reduced if compared to the case of the *single block*. This interaction of the flow turbulence with the macro-roughness elements needs to be evaluated accurately, as it will affect the wake turbulence and hence the flow resistance.

As a final result, for each experiment the ratio of the volume $V_{vn}$ to the total water volume contained between two consecutive blocks $V_{liq}$ is evaluated as a function of the *surface density*, Γ, that is the ratio between the area occupied by a single block and the sum of such area with the bed area contained between two consecutive blocks.

The plot of the results in dimensionless form, shown in Figure 9, reveals a dependence of the volume ratio with the surface density. The quasi-linear trend of the data seems to show a discontinuity in the range of Γ close to 0.4, a value which was shown to be associated to the maximum value of flow resistance developed by a random arrangement of macro-scale elements (Canovaro et al., 2007). In particular, this evidence could suggest that the maximum of flow resistance is associated to the transition from an *isolated roughness* flow condition to a *wake interfering* flow condition.

This last result underlines the need of further experimental observations to understand the effect of many factors such as spatial arrangement of elements, flow discharge and flume slope on the wake interaction phenomena, on flow field characteristics and flow resistance.

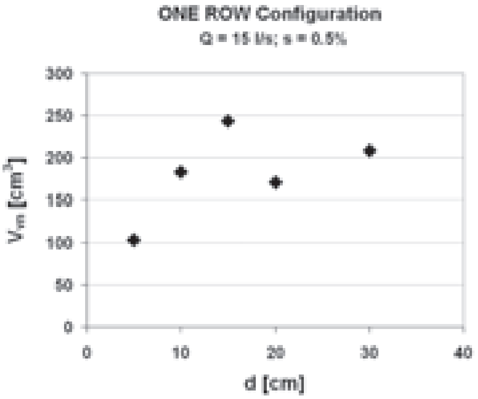

Figure 7. Negative velocity volume as a function of the distance between two elements – linear scale.

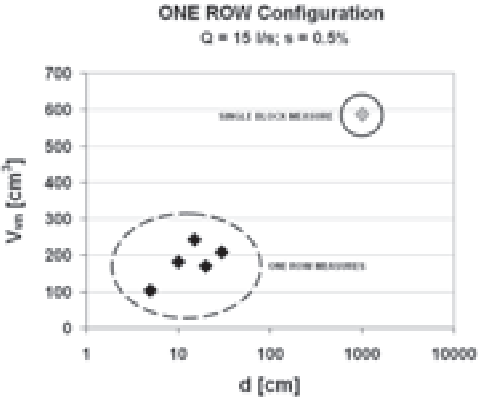

Figure 8. Negative velocity volume as a function of the distance between two elements – log scale.

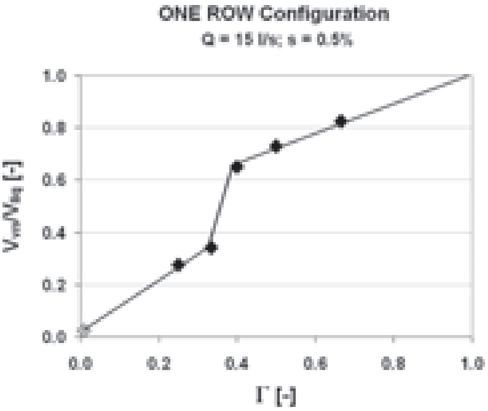

Figure 9. Negative velocity volume to water volume ratio as a function of surface density.

## 4 CONCLUSION AND FURTHER DEVELOPMENTS

In order to investigate the interaction between wakes that originate downstream a macro-scale element, an extensive experimental activity has been carried out. Concrete rectangular blocks have been employed as macro-roughness elements, arranged both as *single block* configuration and as *one row* configuration. In the latter case the distance between two consecutive blocks *d* has been varied in order to analyze the influence of this parameter on wake interference.

Preliminary results herein presented show that the wake developed near the bed downstream the block approaches the free surface as it moves in the flow direction. Considering the wake volume as the water volume where negative velocities occur, it seems that the wake volume increases as the distance between two consecutive blocks increases. Moreover, the results, plotted in the logarithmic coordinates, are arranged along a line that tends towards the experimental point obtained in the case of a single block experiment. Such point could be considered as the asymptotic reference value for one row experiments. Finally, from the results in a dimensionless form it appears that the ratio between the wake volume and the water volume included between two consecutive blocks experiences a discontinuity in the case of a spatial density Γ near to 0.4. It is worth to note that such density value is the same shown to be associated to the maximum value of flow resistance developed by a random arrangement of macro-scale elements.

Further developments and data analysis are necessary in order to catch the role played by the macro-roughness geometric arrangement and flow conditions on wake interference and to verify if the non-monotonic behavior of flow resistance as a function of spatial density in case of macro-scale roughness could be correlated to the wake interference.

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