WAKE INTERFERENCE IN CASE OF MACRO-SCALE ROUGHNESS: PRELIMNARY OBSERVATIONS

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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 play 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 behaviour 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 single test block and on the flow in the case of a row of test blocks, in order to evaluate the wake interference. The velocity profiles are analyzed in order to reconstruct the flow field around the test block to the purpose of estimating the spatial evolution of a steady wake.

Keywords: wake, turbulence, macro-scale roughness.

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 boulder:

- *Isolated-roughness*, when the elements are at relative 'high' distance and no wake interaction occurs. In such case flow resistance is proportional to number of the 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 concentration 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. (2006), 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 behaviour may be related to the transition from a 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

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 (Figure 1):

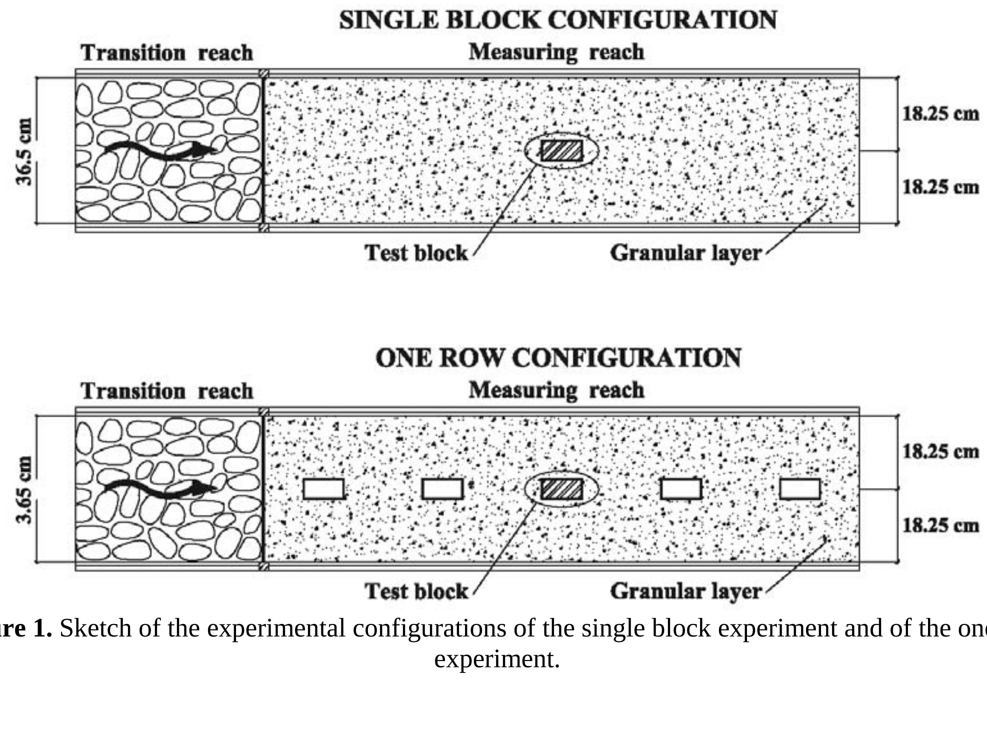

Figure 1. Sketch of the experimental configurations of the single block experiment and of the one row experiment.

- 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.

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.

2.1 EXPERIMENTAL ACTIVITY

The hydraulic conditions of the experimental runs are defined in terms of discharge *Q* and bed slope *S*. For each condition the mean submergence, defined as the mean flow depth *Y* divided by the characteristic dimension of the test block *D*, has been measured, and it is reported in table 1.

***S* [-]** / ***Q* [l/s]**	**0.50%**	**1%**	**1.50%**	**2%**
15	1.50	1.32	1.19	1.11
12.5	1.37	1.26	1.08	1.01
10	1.21	1.08	0.98	0.93
7.5	1.07	0.96	0.86	0.79

Table 1. Mean submergence for the hydraulic conditions of the experimental runs, in the case of single block experiment.

In the present work we focus on the experiments carried out at a discharge *Q* = 15 l/s and a bed slope *S* = 0.5 %. Both single block configuration and one row configuration have been investigated. 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 sketches of the measurement points are reported in Figure 2 for the case of the two experiments reported here: the axes *x* and *y* indicate respectively the transversal and the longitudinal coordinate 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.

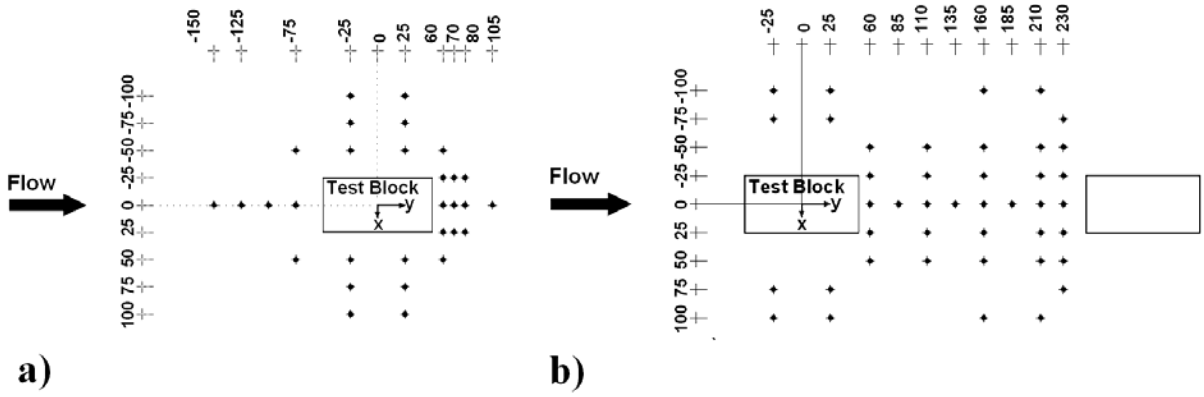

Figure 2. Planimetric sketch of the measurement profiles. a) single block experiment *Q* = 15 l/s, *S* = 0.5%. b) one row experiment: *Q* = 15 l/s, *S* = 0.5%. Longitudinal and transversal coordinate are expressed in mm.

3 RESULTS

The preliminary results of two experiments are here analyzed and discussed:

- single block experiment (*Q* = 15 l/s, *S* = 0.5%)
- one row experiment (*Q* = 15 l/s, *S* = 0.5%)

The longitudinal time averaged profiles of the local flow velocity *u* along the vertical coordinate *z* in front of the test block in the case of the single block experiment are shown in Figure 3, whereas the velocity profiles in the rear of the test block in Figure 4; each profile is characterized by the longitudinal coordinate *y*, which origin is positioned in the center of the test block, at the bed altitude (see Figure 2).

Flow around the test block shows a pattern of vortices formed in its wake and front. The nearly undisturbed velocity profile in front of the test block was measured for *y* = -150 mm (Figure 3). As the flow approaches to the block, the velocity reduces and the profile is affected by the adverse pressure gradient which causes the approaching boundary layer to separate upstream of the obstacle and produces high bed shear stress around the obstacle. Due to the presence of the adverse pressure gradient in front of the block, the flow stopped before the separation line (stagnation point) and moves around. The flow velocity close to the object is strongly decreased, see e.g. the profile for *y* = -75 mm, where the velocity is higher near to the bottom and smaller at the top.

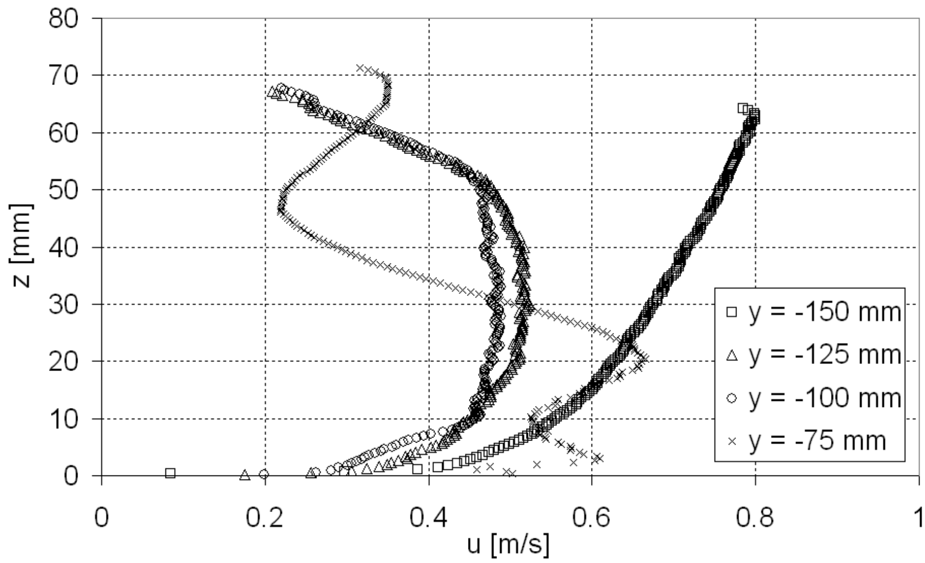

Figure 3. Longitudinal velocity profiles in front of the test block (single block experiment: *Q* = 15 l/s; *S* = 0.5%).

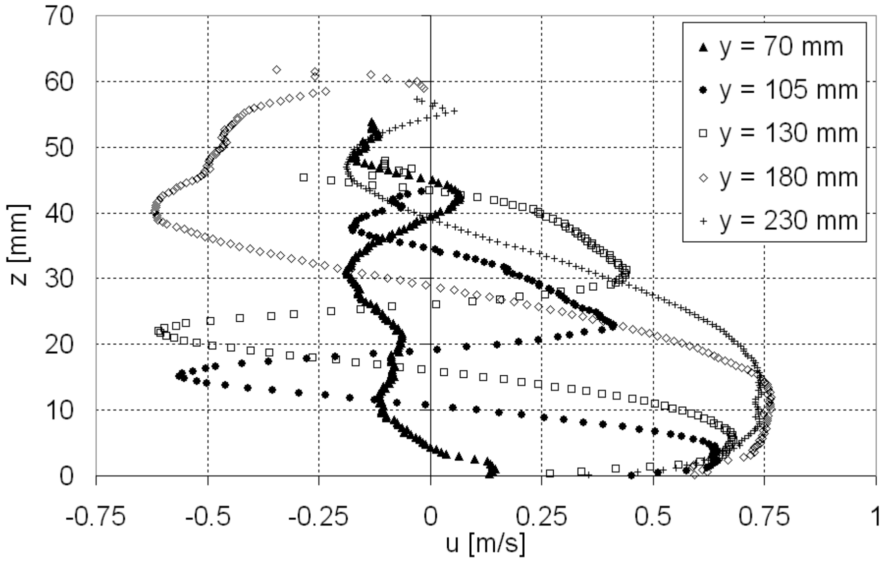

Figure 4. Longitudinal velocity profiles in the rear of the test block (single block experiment: Q = 15 l/s; S = 0.5%).

Part of the flow is passing from the top of the block and, under the influence of the free shear layer, mixes with the wake region. The separated flow from the top of the obstacle joined with the separated flow from the sides thereby forming a strong vortex area.

The recirculation region located downstream of the block has a length of the same order of the longitudinal dimension of the test block. The longitudinal velocity profiles in the rear of the test block (Figure 4) show negative values of the flow velocity which give evidence of the wake region; the recirculation is confined at the bottom in the zone close to the block, while it moves towards the top going downstream.

The longitudinal profiles of the local flow velocity u along the vertical coordinate z between two consecutive test blocks in the one row experiment are shown in Figure 5: in the rear of the upstream block negative values of flow velocity can be observed; moving downstream the velocity slowly increases because the wake diminishes its turbulence and the flow interferes with the external streamlines; close to the front of the downstream block higher velocities are observed near the rough bed and negative velocities are still observed in the upper part of the flow profile due to the interference with the next object.

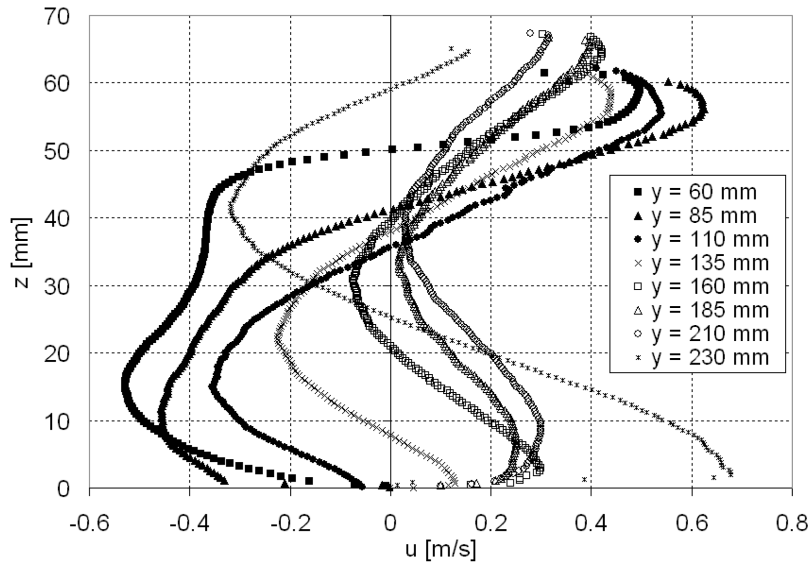

Figure 5. Longitudinal velocity profile between two test blocks (one row experiment: Q = 15 l/s; S = 0.5%).

The profiles acquired in the whole flow field have been processed and analyzed to evaluate the velocity defect in the wake and the effect on turbulent flow structures and on flow resistance.

The defect velocity is evaluated as the ratio between the local value of the flow velocity *u* and the undisturbed local value u_0, referring to the reference velocity profile for which the logarithmic law is valid and measured far upstream of the test block.

The defect velocity in the vertical plane corresponding to $x = 0$ mm and in the case of the two experiments analyzed here is reported in Figures 6 and 7: contour lines show the velocity defect values in the vertical plane; the water surface profiles observed during the experiments are also reported into the Figures 6 and 7.

In the case of the single block experiment, the wake region, where the defect velocity is negative, extends from the recirculation zone just behind the block and moves towards the top going downstream; under the wake region, higher velocities develop and extend further downstream; the length of the recirculation zone was about 1.5-2 *D* and it was attached to the bed with strong backward flow adjacent to the bed.

In the case of the one row experiment, the wake region is larger and closer to the front block: the zone with the minimum velocity is close to the bed, while the higher velocities extend further downstream close to the bed. The interference with the following block has influence on the approaching decelerated flow.

This result allows one to say that if the roughness elements are sufficiently close together, the wake behind each may extend to or nearly to the next element. Furthermore the vortex generation and dissipation phenomena associated with each wake will interfere with those at the adjacent elements, so that the individual effects are not additive as in the case of single roughness element.

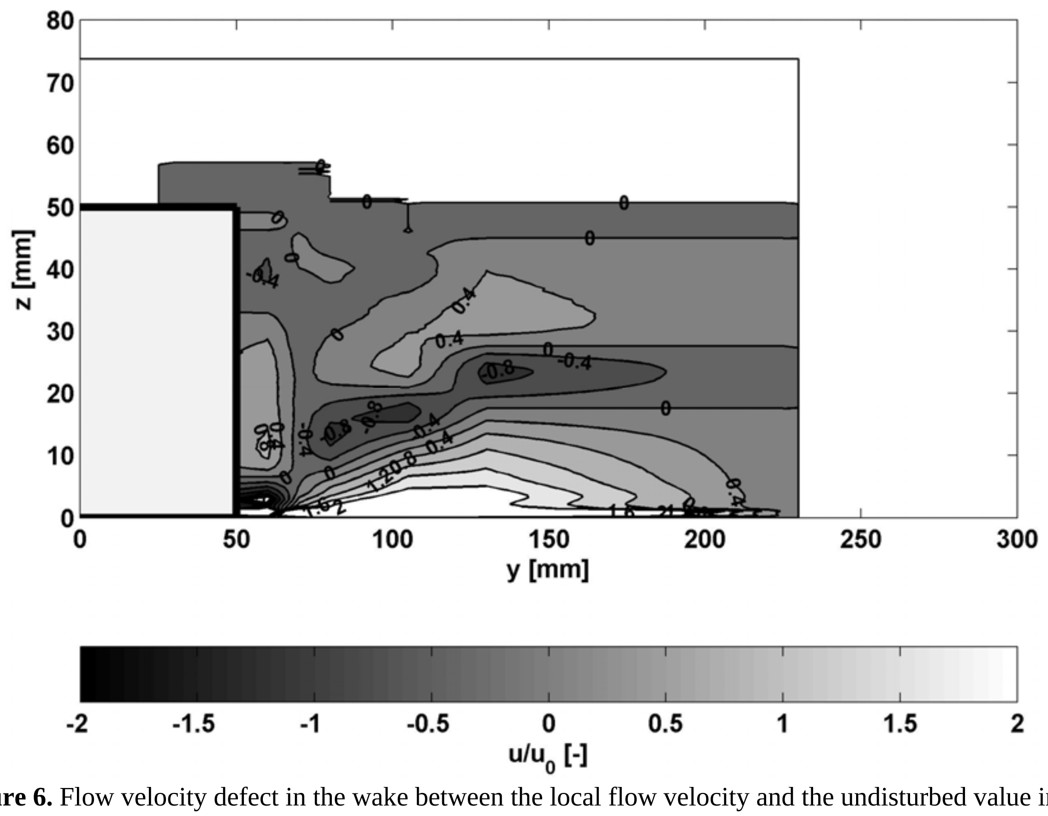

Figure 6. Flow velocity defect in the wake between the local flow velocity and the undisturbed value in the vertical plane $x = 0$ mm (single block experiment: $Q = 15$ l/s; $S = 0.5\%$).

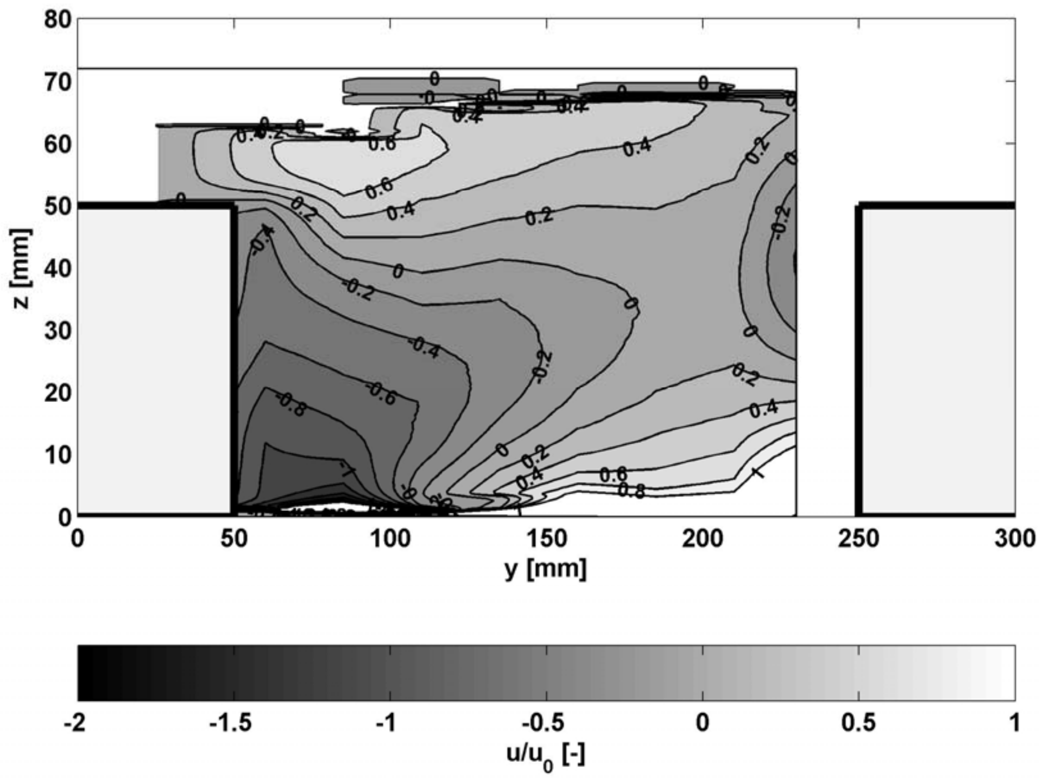

Figure 7. Flow velocity defect in the wake between the local flow velocity and the undisturbed value in the vertical plane *x* = 0 mm (one row experiment: *Q* = 15 l/s; *S* = 0.5%).

4 CONCLUSIONS AND FURTHER DEVELOPMENTS

According to various authors (Bathurst et al. 1981; Colosimo et al., 1988; Baiamonte and Ferro, 1997; Lawrence, 2000; Canovaro et al., 2006) macro-roughness planimetric concentration plays a fundamental role in flow resistance development. In particular this special parameter seems to acts triggering the transition from an isolated-roughness to a wake-interference flow. In order to investigate how macro-scale element wakes interact among themselves, an experimental activity is carried out. Two experiments are herein presented: single block and one row of blocks. Preliminary results about turbulent flow and wake interference show that macro-scale element influence can be observed upstream up to 2.5 – 3 times the test block characteristic dimension *D*, whereas immediately downstream the block a recirculation zone of about 1.5-2 *D* is observed and it is attached to the bed with strong backward flow adjacent to the bed. The analysis of the velocity defect plot indicates that the wake zone extends from the recirculation zone just behind the block and moves towards the top going downstream. In the case of one row experiment the wake zone extends down to the next block, indicating that for this experimental conditions the wake interferes with the next macro-roughness element. Therefore in this case the wake individual effects, such as vortex generation and dissipation phenomena, are not additive as in the case of single roughness element.

The further developments of this study will consist on collecting a more extended experimental set of data, in order to carry out a deeper analysis of the phenomenon and evaluating the influence of various experimental conditions.

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