Surface-PIV measurements on shallow compound channel flows: Coherent flow structures, horizontal mixing and dispersion

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Abstract: An experimental investigation based on PIV analysis of free surface velocities forms the basis for the following analyses of specific features of macrovortices in compound channels. Dynamical properties are seen to strongly depend on the input discharge (low-discharge, intermediate-discharge and high-discharge conditions). The maximum streamwise mean velocity component increases with both discharge/downstream location and the bell-type crossflow profile of the mean streamwise velocity, typical of the low/intermediate discharges, becomes non-monotonic at high discharges (need of new types of self-similar solutions). The mean shear at the transition region decreases with increasing discharge. This leads to the reduction of macrovortex generation at the transition region and a simultaneous increase at the lateral walls. The size of macrovortices in the transition region is closely related to the channel geometry and the shear layer width is found to be almost constant.
Keywords: Compound Channel, Macrovortices, Shear Layer.

Introduction

A great variety of natural water streams and artificial channels can be classified as 'compound channels' since their cross-stream section can be assumed to be characterized by a main central channel and shallow flood plains. We define flows of these streams as predominantly horizontal since their horizontal dimensions greatly exceed the vertical dimension [JIRKA 2004]. Although in bounded shear flows the three-dimensional turbulent eddy size is, typically, limited to the shortest dimension (in this case, the water depth), large-scale, two-dimensional coherent structures with length scales greater than the water depth are observed in a wide range of shallow shear flows [SOKOLOFSKY 2004].

The flow velocity in the flood plains is lower than in the main channel, due to the water shallowness and to the high bed roughness (e.g. presence of vegetation). Thus shearing occurs at the interface between the main channel and the floodplains ('transition region' hereinafter) which may lead to various flow patterns most of which characterized by large-scale vortical structures with vertical axes (macrovortices). Such turbulent structures are liable of the transfer of momentum and mass from the main channel to the flood plains.

The present contribution focuses on the description of the dynamics undergone by macrovortices in a compound channel as part of the overall flow evolution. More specifically we intend to clarify validity and ambiguities concerned with use of *shear layer approach* as the most suited to represent the flow at hand. Further, the results here described will be used as the basis for a theoretical analysis.

Experimental Setup and Data processing

The experiments have been carried out in the laboratory of the Environmental Engineering Department of the University of Genova, Italy using a pre-existing flume. The flume is about L = 20m long and has a width of W = 0.6m, the trapezoidal cross-section with a main channel ($_{mc}$) and two lateral flat floodplains ($_{fp}$) can be seen in figure 1. The cross-section has been subdivided in three sections, each of them have nearly the same width $W_{mc} = 0.2m$, $W_{fp} = 0.19m$. Great care has been dedicated to obtain a perfectly-horizontal channel. The compound channel, including the lateral vertical walls, is made by sheets of polyvinyl chloride (PVC) 1cm thick (Manning roughness n = 0.009 $s^{-1}m^{1/3}$).
Following the main parameters of the experiments: The depth Reynolds number calculated for the main channel to be in the range of $22000 < \mathrm{Re}_{h,mc} < 74000$ and for the flood plain to be in the range of $2500 < \mathrm{Re}_{h,fp} < 37500$, which means that we have fully turbulent conditions. The Froude number is found to approximately range between $Fr_{cc} = 0.6 - 0.7$ and the bed friction is $c_f = 2.9 - 2.0 \cdot 10^{-3}$. Three measurement sections have been selected along the flume respectively located at $x = (2,5,7)m$ downstream of the inlet section.
The ratio between characteristic horizontal (H) and vertical (V) length scales is in the range of $4 < H/V < 20$. This means that the flow can be regarded as intermediate-to-shallow. On these grounds, though fully recognizing the role of secondary flows (e.g. [TOMINAGA 1989]), we proceed to an analysis based on the description of the dynamics evolving at the water surface and take this as a good representation of the dynamics of the shallow flows.

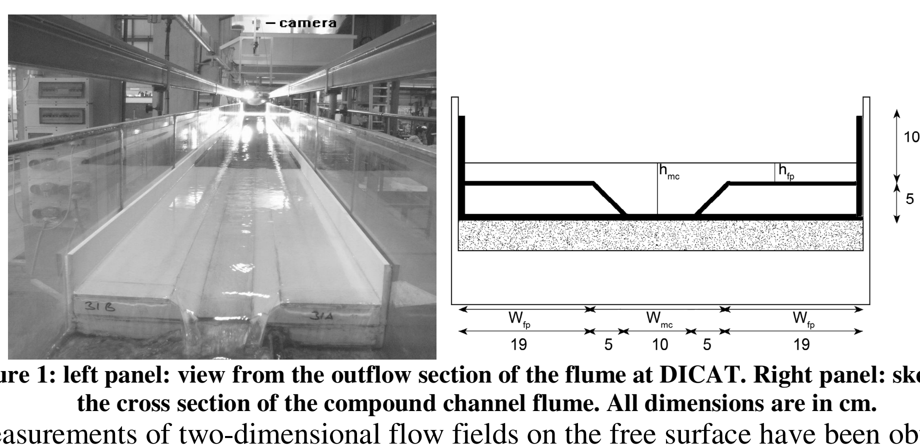

figure 1: left panel: view from the outflow section of the flume at DICAT. Right panel: sketch of the cross section of the compound channel flume. All dimensions are in cm.

Measurements of two-dimensional flow fields on the free surface have been obtained using a PIV system in continuous, single-exposure mode. A digital camera (model:

IDT xS3) with NIKON lens (f=50mm) has been used to record 2000 frames with 100Hz acquisition frequency. The area of interest for the flow measurements has dimensions of about (0.6×0.6) m^2 and (1024×1024) $pixel^2$. The illumination has been provided by three white light incandescent lamps of 1000 Watts each and we used white plastic particles with a mean diameter of 300 μm as tracer. Images were analysed using the software provided by IDT and each interrogation window had physical dimensions of 15.0mm×15.0mm.
The two-dimensional velocity vector outputs of the PIV analysis have been elaborated to extract the main features of the flow under investigation. In particular, we performed an ensemble average on the velocity fields and, then, spatial averages along the longitudinal direction to extract velocity crossflow profiles for each section, see figure 2.
A specific analysis to identify and to track vortical structures has also been carried out. As vortex identification technique we employed the method based on the evaluation of the swirling strength: The swirling strength, defined as the positive imaginary eigenvalue of the local velocity gradients tensor, is large where there is a strong rotation of the flow, i.e. a vortex [ADRIAN 2000]. In two dimensions, the velocity gradient tensor is only a 2 × 2 tensor, which has either two real eigenvalues ($\lambda_r^{1,2}$) or a pair of complex conjugate eigenvalues ($\lambda_{cr} \pm \lambda_{ci}$). Hence, a vortex core is identified by a region where $\lambda_{ci} > 0$. The resulting contour maps of the swirling strength have been used to study the evolution of the macrovortices. With an object-tracking algorithm applied to the contour maps of λ_{ci} (see figure 3) macrovortices are recognized as a single entity, with geometrical characteristics related to the intensity of λ_{ci}. Following the above procedure, we could infer the position of the centroid $X_{centroid}$ of the vortex, the area occupied by the vortex Ω, the radius of the area-equivalent circle R_{eq}, and other geometrical characteristics of interest, e.g. the eccentricity ε of the vortices and the maximum radius $R_{\max}$, the inclination angle θ with respect to the mean flow direction x. When required, the analysis has been refined to separate vortices generated in the transition region −0.2m≤y≤0.2m (transition region vortices) and at the wall boundary layers y<−0.2m and y>0.2m (wall vortices).

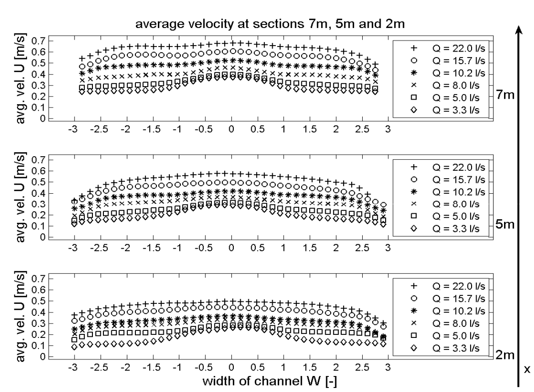

figure 2: transversal velocity profiles for different downstream positions x = (7,5,2) m and discharges Q = (3.3,5.0,8.0,10.2,15.7,22.0) l/s.

Probability Density Functions (PDFs) have been obtained by normalizing the occurrence of the vortices with the total number of vortices per experiment. The total number of vortices used for the analysis is in the range of 200 and 400 per experiment with an average and overall (i.e. without distinguishing transition vortices from wall vortices) shedding frequency increasing with the input discharge from 1.0Hz to 2.1Hz.

Mean Flow and Macrovortices

One of the main characteristics of a compound channel flow is the difference in velocity between the main-channel flow and the floodplain flow. Such difference is essentially driven by the bottom friction which, being inversely proportional to the flow depth, more effectively slows down the floodplain streams than that flowing in the deeper main channel. Inspection of figure 2 well illustrates the mean velocity reduction occurring over the floodplains, the growth of the mean velocity with both the flow discharge Q and the downstream distance x.

Other features are also evident. For example, the reduction of the transversal shear at fixed x and the near-wall sudden velocity decay because of the no-slip condition at the lateral walls and the non-monotonic profiles observed at the most downstream section x = 7m for flow rates higher than Q = 10.2l/s. While the former suggests a progressive reduction with both x and Q of vortex generation at the transition region balanced by an increasing generation at the lateral boundaries, the latter clearly indicates that a self-similar solution, if any is possible, has to be sought with a shape more complicated than that given by the usual hyperbolic functions.

Since it is well recognized that the maximum shear intensity at the transition region is the most important parameter governing the flow, we investigate its role through inspection of figure 4. The left panel clearly illustrates the reduction in flow shearing at the transition region with increasing flow intensity. This is also reflected in the reduction of macrovortices generation at the transition region and a simultaneous increase at the lateral walls (see figure 5 and next section).

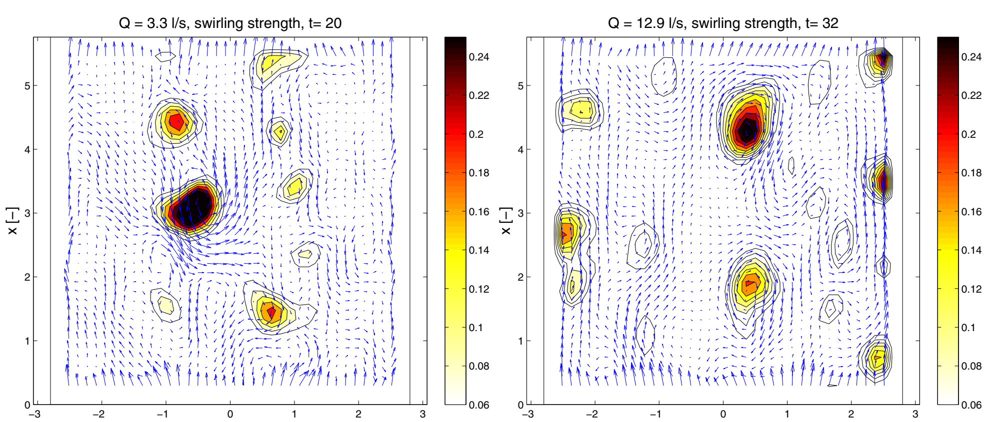

figure 3: swirling strength and velocity fluctuations distribution of sample ensemble-averaged flow fields at x=7m for a low discharge Q=3.3l/s (left panel) and a high discharge Q=12.9l/s (right panel) case. Velocity fields are derived from a space-time decomposition of the instantaneous velocity field and different colors correspond to the magnitude of the swirling strength.

It is also evident (within the experimental limits) that the shear does not increase (rather it likely decreases) with the downstream distance. This fact can also be seen in the right panel of figure 4 where the shear layer thickness $\delta = \Delta U / U_y$ built with the velocity difference across the shear layer $\Delta U = U_{\max} - U_{fp}$ and the velocity gradient U_y at the inflection point, is drawn as a function of the downstream distance.
Now we focus, also on the basis of the results of the previous section, on the main features of the macrovortices. It is first fundamental to assess the characteristics of their generation which, as above mentioned, seems to be mainly concentrated in the transition region for low discharges and at the lateral walls for high values of Q.
Macrovortices of different sizes are generated in dependence of the flow intensity Q and of the generation region. To detail such dependencies we have analyzed both the PDFs of the vortex radius (left 4 rows of figure 5) of both transition region vortices (represented by lines with diamonds) and wall vortices (represented by lines with crosses) and the vortex radius as function of both Q and x (right panels of figure 5). For low discharges (Q < 5l/s), vortices are seen to reside mainly in the transition region at all three considered sections and with typical size in the range (0.025 – 0.035) m. For large discharges (Q > 10.2l/s) macrovortices both increase in size and frequency over the floodplains, the transition region exhibiting a decreasing vortex content.

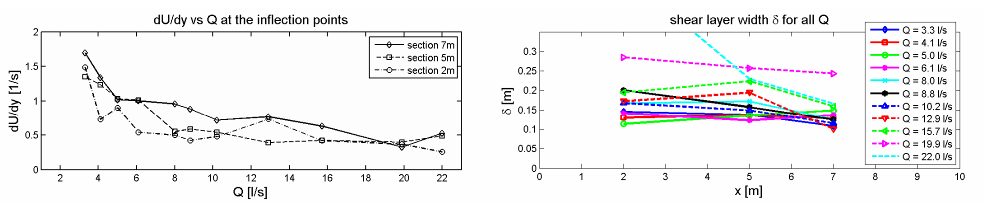

figure 4: mean flow shear dU/dy at inflection point (left panel) and shear layer thickness δ as a function of downstream distance x (right panel) .

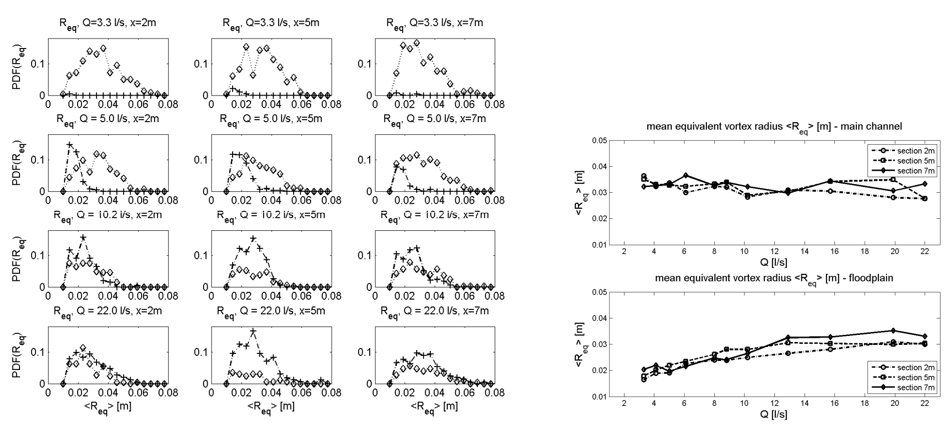

figure 5: Macrovortex size. the left panel show the PDF of the equivalent radius R_{eq} for discharges Q=(3.3,5.0,10.2,22.0) l/s. The lines with diamonds refer to structures residing in the transition region while the lines with crosses to those residing in the floodplains. The right panel report the mean vortex radius as function of Q. transition region vortices (upper panel) are spearated from wall vortices (lower panel).

The fundamental result is, however, reported in the right panels of the figure: the mean vortex radius, weakly-decreasing in size for Q < 10.2l/s, is always in the range 0.020m≤ Req ≤ 0.037m, which well compares with the transversal size of the transition region (0.05m), for all values of x.

Conclusions

A detailed and extensive experimental investigation based on PIV analysis of free surface velocities has been made to reveal the fundamental features of the flow characterizing a straight compound channel from the inception to fully-developed conditions. Specific focus was on the evolution of the transition region shear layer which is mainly dominated by macrovortices and pointing out similarities/differences with a true free shallow shear flow. The main findings of this work can be summarized as follows:

• the maximum streamwise mean velocity component increases (approximately linearly) with Q and x, while the bell-type crossflow profile of U, typical of the low/intermediate discharges, becomes non-monotonic at high discharges (hence the need of new types of self-similar solutions). The mean shear at the transition region decreases with increasing Q and leads the reduction of macrovortex generation at the transition region and a simultaneous increase at the lateral walls;

• the macrovortices radii range between 0.025m and 0.035m, i.e. clearly scaling with the crossflow extension of the transition region;

• the global dynamics of a straight compound channel cannot be entirely explained by a shear layer approach i.e. the flow largely differs from that obtained by the meeting of three parallel streams of different velocity (fast stream in the main channel and two slow streams at the floodplains). The compound channel topography and boundaries force a non-monotonic velocity profile, a shear layer thickness weakly decreasing downstream, macrovortices generated at the transition and at the lateral wall with size almost independent of the streamwise coordinate.

All the above suggests that more analyses should be devoted to the understanding of the global flow in a compound channel in addition to ongoing studies of local features.

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References

R.J. Adrian, K.T. Christensen, and Z.C. Liu, Analysis and interpretation of instantaneous turbulent velocity fields, Expts. in Fluids **29**, 275-290 (2000).

G.H. Jirka and W.S.J. Uijttewaal, Shallow Flows: a definition, Shallow Flows, 1-13 (Balkema, Leiden, NL, 2004).

S.A. Socolofksy and G.H. Jirka, Large-Scale Flow Structures and stability in shallow flows, J. Environ. Eng. Sci. **3**, 451-462 (2004).

A. Tominaga and I. Nezu and K. Ezaki and H. Nakagawa, Turbulent structure in straight open channel flows, J. Hydr. Res. **27**(1), 149-173 (1989).