MEASUREMENT OF 3D FLOW FIELD IN A 90° BEND WITH ULTRASONIC DOPPLER VELOCITY PROFILER

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Keywords: Ultrasonic Doppler Velocity Profiler (UVP), velocity measurement technique, scour in bends, 3D flow field, flow mapping, velocity distribution.

ABSTRACT

In the frameset of a research work on scour in river bends, the influence of vertical ribs placed on the outer sidewalls on the maximum scour depth and the modification of the flow field was studied. The velocities were measured by means of an Ultrasonic Doppler Velocity Profiler, which allows an instantaneous measurement of the 1D velocity profile over the whole flow depth. The measurement probes were mounted on a support in groups of three, allowing the measurement of the 3D flow field. The probes were inclined at 20° to the vertical. The velocity measurements were integrated in an acquisition device also permitting the measurement of the water- and bed-levels with automatic positioning of the probes at about 1500 measurement points.

The secondary flow in river bends induces radial velocities of about 10% of the value of the tangential velocities (which are of positive and negative sign). A method is presented to measure velocities exceeding the measured velocity domain due to a shifting of the raw Doppler signal. Furthermore, the data treatment to obtain the average flow field in the tangential direction and in the cross section is described.

A brief description of the obtained results is given. The flow field in a river bend undergoes some important modifications compared with the one in a straight river reach. These modifications as well as the influence of the vertical ribs on the velocity profiles are presented and briefly discussed. The analysis of the flow field allowed observing a secondary outer bank cell located at the free water surface having a bank protection effect. With increasing wall roughness, this cell gets more important.

1. INTRODUCTION

In the framework of a study on scour (erosion in river bends), the 3D-velocity field was measured. The aim of the study was to investigate the flow distribution and the scour depth in a bend with special emphasis on the influence of vertical ribs applied to the outer wall serving as macro-roughness (Figure 1). These measurements were performed in a 1 m wide 90° bend (Radius of 6 m) at various longitudinal bed slopes and discharges for different rib spacings and depths, as well as without ribs.

2. ACQUISITION SYSTEM

2.1 Components of the acquisition device

2.1.1 Hardware

In order to measure the 3D velocity field, a measurement frame (2 x 2 m, Figure 2) was put on the channel every 15° at eight predefined positions. Within the measurement frame, a regular grid of measurement points (9 x 9 cm) was chosen to perform the measurements.

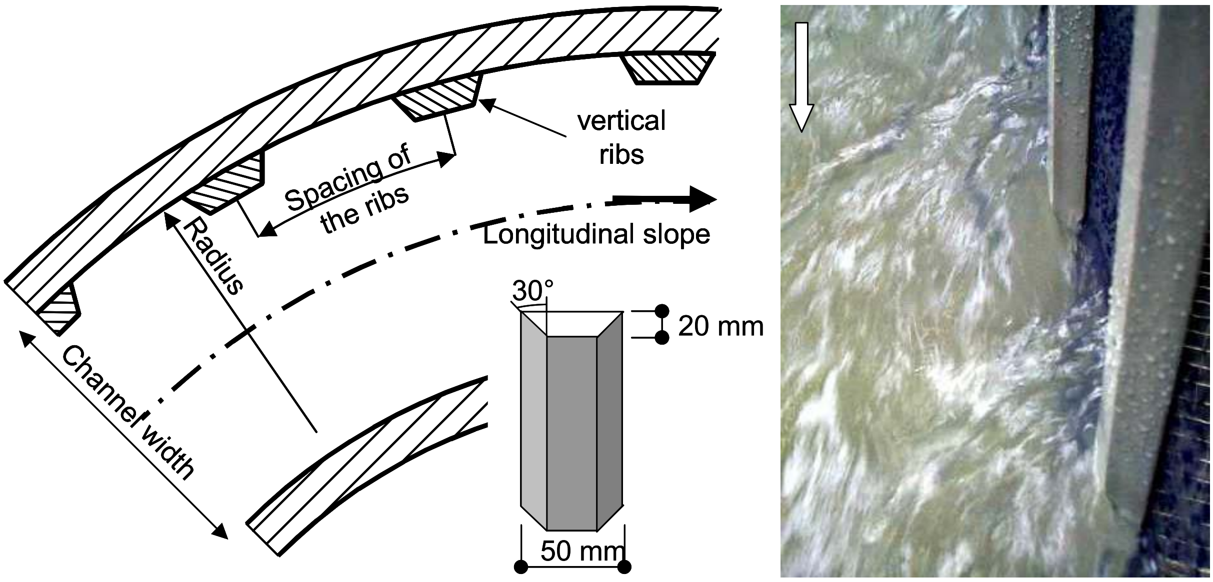


Figure 1 Vertical ribs (macro-roughness) applied on the outer sidewall

The velocities were measured with an Ultrasonic Doppler Velocity Profiler (Metflow, Model UVP-XW) allowing for an immediate obtention of a 1D-velocity profile over the whole channel depth (see METFLOW, 2000). To measure the 3D-flow field, three 2 MHz-probes were mounted on a probe support plate (Figure 2 and Figure 3). Since the number of measurement points was very high (about 1500 points over the whole channel), three plates were mounted on the measurement frame, permitting the simultaneous recording of three groups of three 1D profiles (constituting one 3D profile) which accelerated the data acquisition.

A multiplexer (Figure 2, on the left of Nr. 5) allowed for the switching from one UVP-probe to another.

Due to the complexity of the flow field in bends, several specific problems had to be solved: (1) The measured velocities in the tangential direction are rather high (up to 1.5 m/s), (2) the radial velocities are of an order of magnitude smaller than the velocities in the tangential direction and (3) the radial velocities are both positive and negative due to the secondary flow. Therefore, the scale of the measurements had to be fixed to allow for good quality recording of high as well as small records with positive and negative values.

Two measures were taken to reduce the value of the measured velocity. (1) The UVP-probes were inclined at a 20° angle, thus reducing the highest velocities to 34% (sin 20°). The inclination was not increased to higher values since a very small error in the frame geometry would lead to an important measurement error. Furthermore, this inclination still gives a satisfying resolution for low velocities. In spite of this, some velocity peaks were somewhat too big to be measured. (2) As a result, an interesting characteristic of the used Doppler measurement was explored. If the measured velocity is higher than the maximum velocity (similar for the minimum velocity), the UVP shifts the measured value by 2 times the velocity range into the negative measurement domain (ROLLAND, 1995). If the sign of the velocity is known, the recorded velocity profile can be corrected by shifting the negative values into the positive domain again. This was done for the high velocities in a tangential direction whose sign was clearly given.

Since the UVP-probes could not be placed vertically, the vertical control volume has a conic shape with a diameter of up to 3 to 6 cm, depending on the distance to the measurement plate.

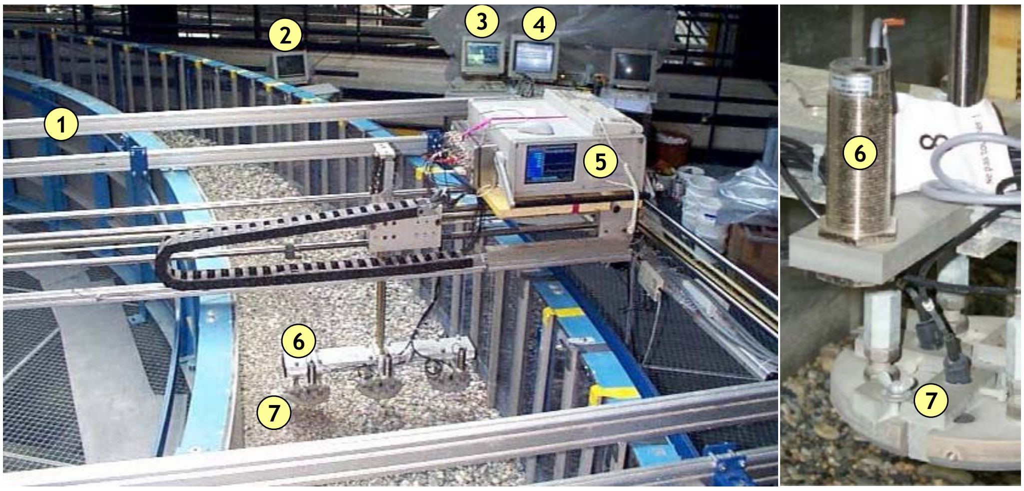


Figure 2: The measurement frame with probe support
1 Measurement frame, 2 Discharge controller, 3 Frame controller, 4 Level acquisition, 5 Velocity acquisition, 6 Levelling probe, 7 Velocity probe and support

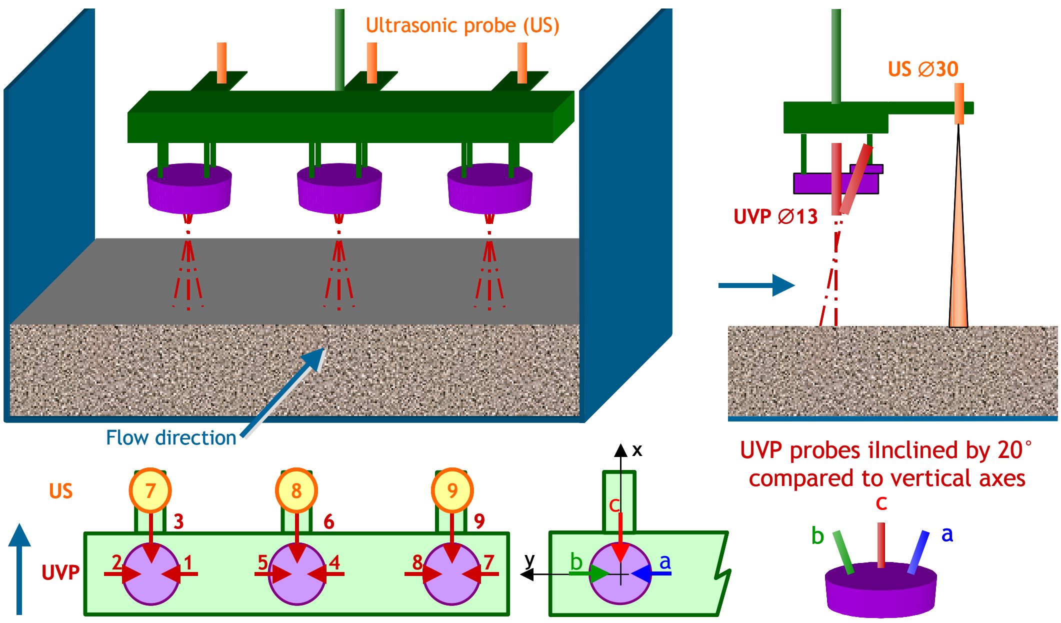


Figure 3: Scheme of the probe support for UVP-Doppler velocity measurement and US bed levelling

2.1.2 Software

A special software was developed to control and automate the whole acquisition process including movement of the measurement frame to the desired position, recording of water and bed levels and recording of the velocity field (Figure 4).

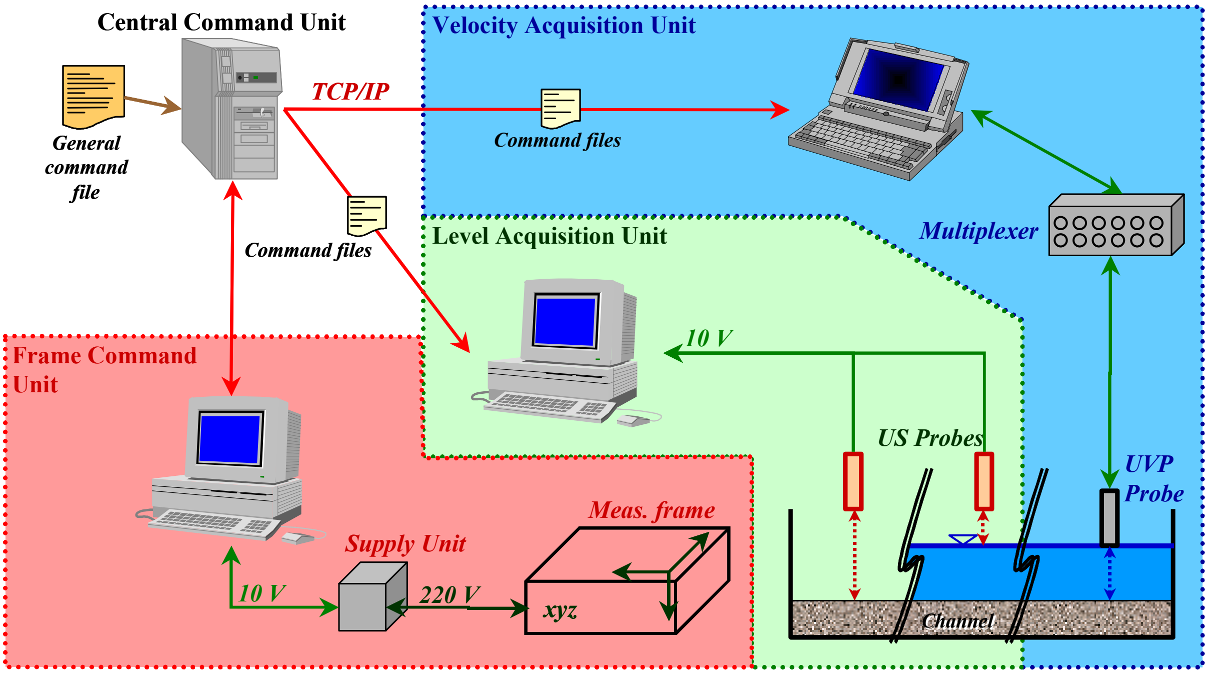


Figure 4: Scheme of the acquisition device

A central command file – fixing frame positions and measurements to be performed – was introduced into the central command unit. This Unit generated small data packages, which were sent to the three different devices[1]. A direct connection to the measurement frame allowed for the control of the measurement location. A special tool introduced the commands into the level acquisition device and into the UVP over the local network. All operations were recorded in a log-file.

2.2 Velocity measurements

In the present study, the main interest is the average flow field. Therefore a rather short measurement was performed. For each 1D-velocity profile, 64 data points (in time) were recorded with a resolution of 128 points (in space). The multiplexer switched to the next probe after 64 measured profiles. Consequently the measured flow field is not an instantaneous 3D-field, but for average values, it can be assumed to be constant considering the short recording time. The acquisition frequency was at about 70 Hz, which would even allow an analysis of turbulence characteristics for one probe for longer samples; therefore longer recordings were performed over 2048 samples (in time) for some selected cases. A set of nine 1D-profiles performed at a given frame location was stored in a specific binary file for later treatment and analysis (§ 3).

[1] The three devices were located on different machines due to incompatibilities between data acquisition cards.

3. DATA TREATMENT

The three 1D records at the three positions were extracted from the raw data file (Figure 5). The high velocities in tangential direction with a negative sign[2] were then corrected so as to be located in the positive range.

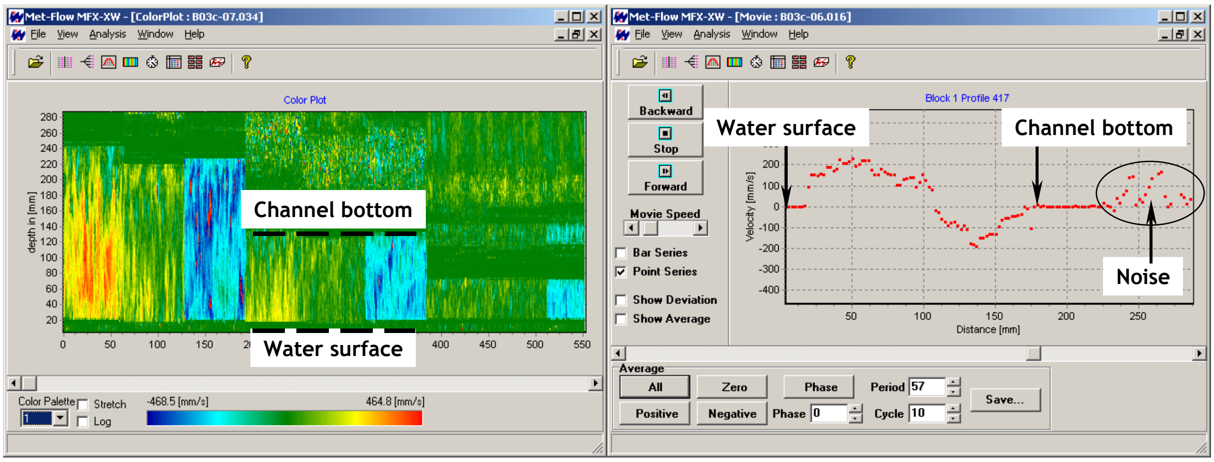


Figure 5: Used UVP Software showing a sample file

Next, the measured components at a given location had to be projected into a cylindrical coordinate system fitting the bend (tangential, radial and vertical velocities). Assuming that the measured velocity components are a, b and c (see Figure 3), the velocity components in one point are given with

$$u = \frac{a + b - 2 \cdot c}{2 \cdot \sin\alpha}, \quad v = \frac{-a + b}{2 \cdot \sin\alpha}, \quad w = \frac{a + b}{2 \cdot \cos\alpha}$$

The thus obtained velocity components cover the whole measurement depth. As can be seen on Figure 5, the bottom of the flume is clearly detectable. Due to the high amount of velocity profiles, it is useful to be able to detect the bottom automatically. In the present study the ground was fixed at the level for which the two following conditions applied: the velocity as well as the variance are close to zero (absolute value below a given threshold). Another way in which to detect the bottom consists of looking for the peak of the bed shear stress, which is proportional to the derivation of the velocity over the depth du/dz. Both approaches give excellent results.

4. DATA ANALYSIS

A detailed analysis of the 3D velocity field in a bend can be found in HERSBERGER (2002). A brief summary of the flow field analysis is presented hereafter.

4.1 Modification of flow field in bends

4.1.1 Tangential velocities

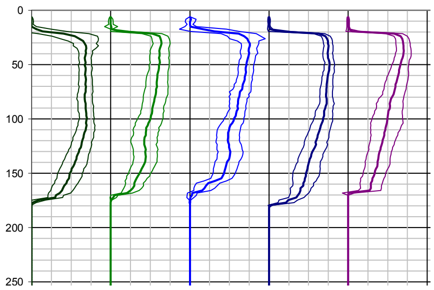
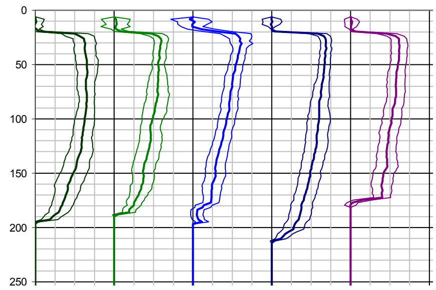
The velocities in a tangential direction (along the channel axis) are somewhat modified in the bend. Instead of a classical “log”-velocity profile as can be seen on top in Figure 6, it undergoes the following modifications in a curved channel. The maximum velocity is no longer found close to the free water surface but close to the bed surface, particularly in the

[2] Values close to zero were not corrected since some near bed fluctuations are possible.

scour holes; this can be very well seen in the cross-section 40°, in the second profile from the left. The highest velocities are now found in the outer half of the cross-section.

With macro-roughness, the near bed velocity is reduced and the maximum velocity shifts towards the free water surface (Figure 6 right, first two profiles at the outer bank).

The measurements showed that the highest main velocities are located in a straight reach next to the free water surface. In the bend, this zone of maximum velocity first shifts towards the outer sidewall where it plunges down along the wall towards the channel ground. At the maximum scour location, high velocities can be observed close to the ground (Figure 7, left).

<table>
<tr><th>XS</th><th>Without macro-roughness</th><th>Ribs spaced at 2 x the mean water depth</th></tr>
<tr><td>10°</td><td>
</td><td>
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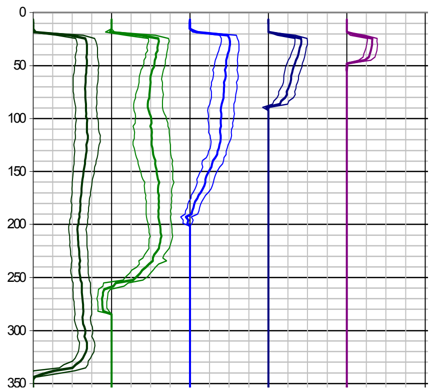
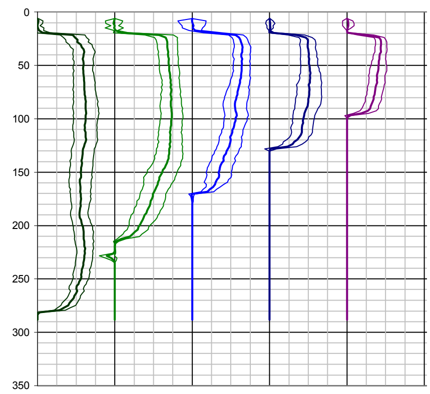
<tr><td>40°</td><td>

outer bank inner bank</td><td>

outer bank inner bank</td></tr>
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Figure 6: Mean velocities and standard deviations in tangential direction. View in the downstream direction. Left profile at 90 cm from the outer bank, radial distance between profiles 180 cm. Vertical axis: free water surface in mm.

With macro-roughness, the zone of maximum velocity remains close to the surface over the whole bend with a rib spacing of about two times the mean water depth. By introducing additional ribs, (spaced at about the mean water depth) the maximum velocity moves towards the channel ground, but at fair distance from the outer wall (at about the average flow depth). For the smallest rib-spacing, the high-velocity zone gets even closer to the ground, but once again at fair distance from the outer side wall. Since the highest velocities are kept away from the outer bank, wall foundations are less endangered by scouring.

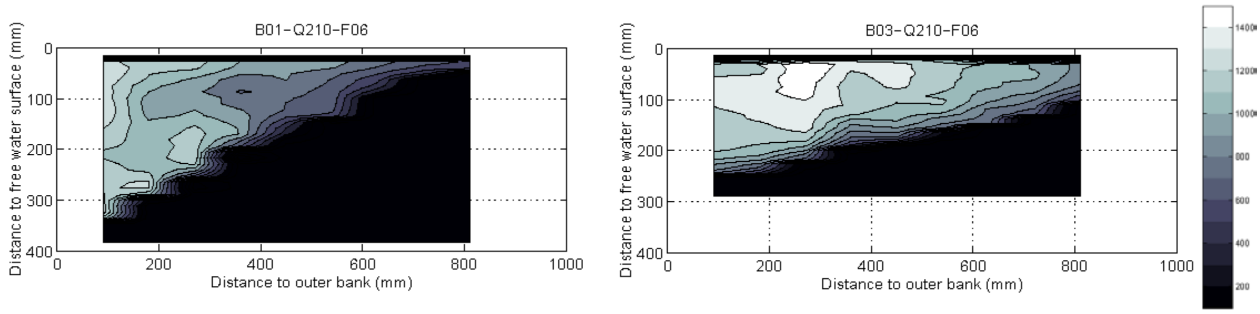

Figure 7: Tangential velocities at 40° without macro-roughness (left) and with ribs spaced every 2° (right); velocities in mm/s.

4.1.2 Velocities in the cross-section - secondary current

The flow field in the cross-section (radial and vertical components combined) shows the growth of the secondary current starting just after the beginning of the bend, increasing in the downstream direction and reaching its maximum intensity in the first scour hole (Figure 8, top). Towards the second scour hole, the main cell again becomes greater, but not as great as for the first scour. The near bed radial velocities are of the same order of magnitude over the whole channel (about 10% of the tangential velocity components).

By placing ribs at the outer side wall (every 4°), a secondary current of almost constant intensity over the whole bend is well visible.

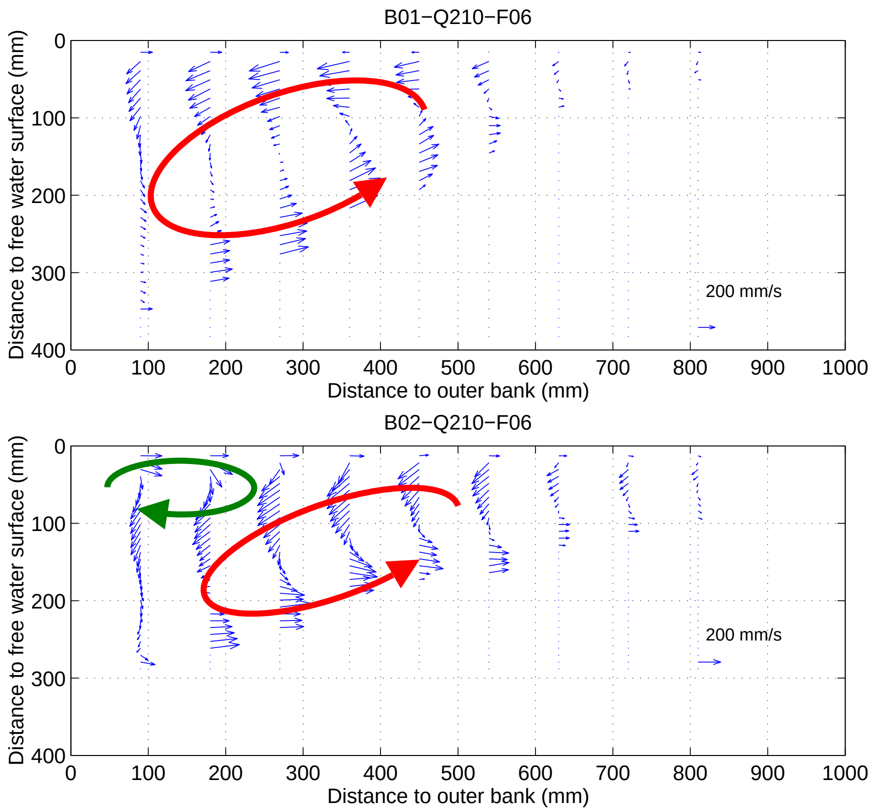

Figure 8: Main and inner bank secondary cells in the first scour hole (no macro-roughness, on top) and main secondary cell and outer bank secondary cell protecting the wall of the channel (rib spacing 2°) at 70° (bottom)

At the outer bank at the free water surface, a very small secondary cell (outer bank cell) becomes visible (Figure 8). This cell was described by BLANCKAERT & GRAF (2001). For the tests, this cell keeps the same intensity over the whole bend. If more ribs are added (2°), the cell increases. But if the rib spacing is too dense (1°), it decreases again, but does not disappear (see 55°). Knowing that the scour reduction is most important for rib spacings of 4 and 2°, it can be concluded that the cell reaches the greatest size for the tests with the most important scour reduction.

Blanckaert observed the highest tangential velocities at the interface between the two cells. If we compare Appendix 11.4 with 11.5 we find high velocities at the interface, but the highest velocities occur inside the main secondary cell either towards the free water surface or near the outer bank.

The intensity of the radial velocity components on the ground with all rib spacings is of the same order of magnitude as without macro-roughness. This leads to the conclusion that the radial velocity components cannot explain the difference in the scour depth. If the radial components cannot explain this difference, then the secondary current cannot explain it either, even if it contributes to the erosion process. But looking at the tangential velocities, we see a significant reduction of the near bed velocities if we apply vertical ribs on the outer bank. Furthermore the tangential velocities are about 10 times bigger than the radial ones. Therefore we must to conclude that the modification of the tangential flow field seems to be a determining factor for the reduction of the scour due to macro-roughness.

ACKNOWLEDGMENTS

This research is being sponsored by Met-flow SA, Lausanne, Switzerland, the Swiss National Science Foundation under Grant No. 2100-052257.97/1 and the Swiss Federal Office for Water and Geology (FOWG).

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NOTATION

a, b, c	velocity components in probe direction
u, v, w	velocity component in tangential, radial and vertical direction
α	inclination angle of the probes compared to a vertical line (20° in the present study)