Secondary flow and velocity redistribution by bubble screens in open channel bends

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ABSTRACT: In rivers flowing in their own alluvial deposits, the curvature induced circulation results in a cross section with deep outer bends and shallow inner bends, which reduces the depth and width of navigation. In the past various solutions have been proposed to increase the width of navigation through temporary dredging and/or costly non reversible river engineering works. The present paper presents results of preliminary experiments to reduce the influence of the curvature induced circulation by means of a counteracting circulation, generated by a bubble screen along the outer bend. With a bubble screen in operation, two counter rotating circulation cells exist, with a downward flow at the junction of both cells. Due to the presence of the bubble induced circulation, the core of maximum bed shear stress shifts in the direction of the inner bend, while the curvature induced circulation is crushed in inward direction. Increasing the width of navigation seems feasible although many questions still have to be resolved.

1 INTRODUCTION

It is well known that in natural rivers, the bottom configuration is seldom flat. On all spatial scales, bed forms develop, varying from very small ripples to very large alternating bars. For an elaboration of the scale-issue, we refer to Seminara (1995), De Vriend (1999) and Baptist (2005). This paper concentrates on the mega-scale, which is the scale of bars rather than dunes of ripples.

In straight rivers, a pattern of alternating bars is often found, depending on the width-to-depth ratio of the channel. This is a *free* instability, which arises spontaneously due to the fact that there are always small perturbations present on the river bed which grow to finite amplitudes if the conditions are right (for a theoretical analysis of free bars, see for instance Schielen et al 1993).

In open-channel bends, the curvature of the channel gives rise to a *forced* instability which forms the so bar pool bed topography with a point bar in the inner bend and a scour hole in the outer bend (Fargue 1868, Odgaard 1981, etc).

This paper will focus on open-channel bends, although the technique presented can also be applied in straight rivers.

For this paper, it suffices to mention that the bend topography is mainly shaped by the interaction between the velocity distribution, the secondary circulation and the bed topography itself.

This secondary circulation, also called spiral flow or helical flow, is a typical feature of flow in open-channel bends (see Fig. 1, Van Bendegom 1947, Rozovskii 1957, de Vriend 1981, Blanckaert and de Vriend 2003, 2004).

Point bars in the inner bend often cause hinder for shipping because the width of the navigation channel is decreased. This problem is of special importance for the Dutch river Waal (one of the Rhine-branches), which is one of the main shipping routes in Europe. For the Waal, the problems are even more pregnant because in the upper reach, there are several sharp bends which induce large point bars. There are in principal two ways to avoid the existence of point bars: influence the flow, or protect the bed.

The flow can be influenced by the construction of bottom vanes, which actually prevent the secondary circulation to develop. A disadvantage of this method is that it is a fixed construction on the bed, and hence it is a possible threat for the ships. Bottom vanes are applied in for instance Bangladesh, see

Hossain et al (2005) and Jongeling and Flokstra (2001), and, in the past, have been considered in the Dutch river IJssel. However, due to the aforementioned threat to the ships, they have never been constructed.

A method which acts on the bed is the construction of a fixed layer in the outer bend. The mechanism is that due to the fixed layer, the outer bend can no longer erode, and hence no material can be transported to the inner bend. Thus, point bars can not develop. Disadvantage of this method is again that it is a fixed construction. As the bed-level in the eastern part of the Netherlands is decreasing, the river Rhine cuts itself deeper in the land and hence, a construction like a fixed layer may also become an obstacle for shipping.

A third method to prevent point bars is the construction of groynes with a limited height ('bed-groynes' or submerged groynes). The maintenance of these under-water groynes however, is far from easy and they are often destroyed under high-water conditions.

In this paper, we describe the method and results of a new, and non-permanent way to perturb the secondary circulation. The central idea is to counteract the downward movement of the secondary circulation by releasing rising air bubbles. The bubble screen drags the flow upwards, and hence, the secondary circulation is perturbed. Figure 1 schematically illustrates this technique.

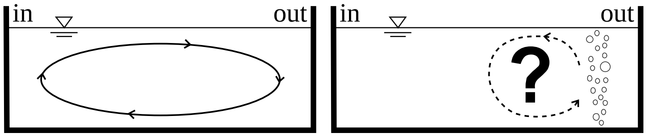


Figure 1. Conceptual sketch of (left) secondary circulation in open-channel bends; (right) the bubble-screen technique.

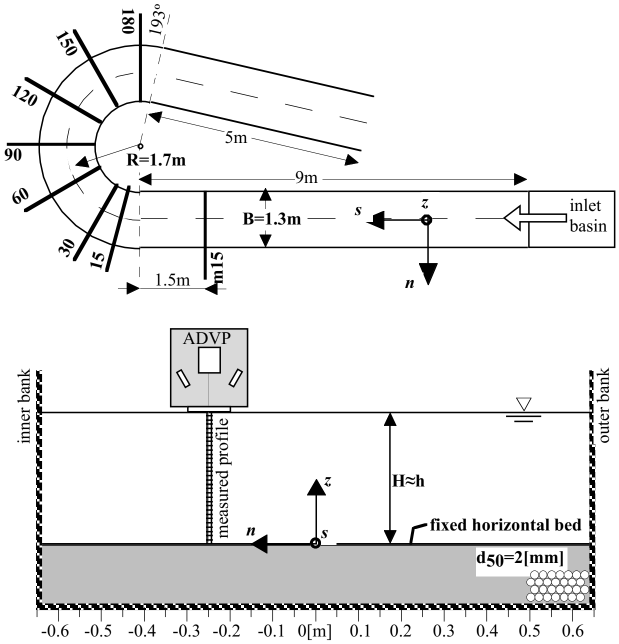
At forehand, it is not clear how the bubble screen will influence the flow pattern. The main research questions of this paper therefore are:

1. Can a bubble-screen counteract the development of the curvature induced secondary circulation ?
2. What are the characteristics of the remaining flow pattern?

This paper briefly describes the laboratory flume and the experimental conditions, presents the results and discusses them with respect to the navigable width.

2 EXPERIMENTS

To investigate the influence of a bubble-screen on the secondary circulation in a bend, experiments were carried out in the strongly curved laboratory flume at the École Polytechnique Fédérale de Lausanne (EPFL) in Switzerland. The curved flume, see Figure 2, consists of a straight inflow reach of 9m, a 193° curved reach with a 1.7m radius of curvature for the centreline and a straight outflow reach of 5m. The width of the flume is 1.3 m, with a rectangular cross section. The bed slope of the inflow reach is 0.22%, while the bend and the outflow reaches are horizontal. The flume bed and the outer bank were artificially roughened with sand, having an average grain size of 2mm, glued to the surface, whereas the inner bank was made of Plexiglass.



Q [l/s]	H [m]	U [m/s]	$1/\sqrt{C_f}$ [/]	Re [10^3]	Fr [/]	R/B [/]	H/R [/]	B/H [/]
89	0.159	0.43	10.8	69	0.35	1.31	0.094	8.2

Figure 2. Experimental set-up, reference system, ADVP and hydraulic conditions. B= flume width, H= water depth, R = radius of curvature, U = flow velocity, Q = discharge, Re = Reynolds number, Fr = Froude number.

From earlier experiments in the flume (see Blanckaert 2002a) extensive reference data with respect to the unperturbed secondary circulation, is available for a water depth of 0,159m. To be able to compare results of the experiments at hand with the earlier experiments similar flow conditions were installed, see Figure 2.

For the bubble-screen, use was made of a porous tube, which was placed from the bend entry till the bend exit at a distance of 0,20 m from the outer wall at the location where the downward velocities were largest in the reference experiments without bubble-screen. The holes in the tube are very fine and located on both sides of the diameter, approximately 3 mm apart in longitudinal direction, resulting in bubbles with a diameter of 0.002m till 0.015m. The tube was on both sides connected to the same compressor enabling a more or less constant air pressure along the whole length of the tube. The pressure in the tube was measured and could be regulated with a valve. Preliminary tests indicated an optimal pressure of 3 bar, which fortunately coincided with the recommended pressure for the tube.

For the flume a curvilinear coordinate system is defined with *s*-direction along the centreline of the flume, a transversal axis *n*, perpendicular to the centreline, positive in outward direction and a vertical *z*-axis perpendicular to the plane through *s* and *n* and positive in upward direction, see Figure 2.

Water levels, bed levels and flow velocities were measured in the cross-sections at an angle of 15°, 30°, 60° 90°, 120°, 150° and 180° in the bend and included the transversal locations, n = [-0.5, -0.4, -0.3, -0.2, -0.1, 0, 0.1, 0.2, 0.3, 0.4, 0.5] m.

The flow velocities, either with or without bubble-screen, were measured with an Acoustic Doppler Velocity Profiler (ADVP), designed at EPFL. Sample time was 180s. The system is based on a central emitter (see Figure 3) which periodically sends an acoustic signal with a frequency of 1 Mhz in the vertical downward direction. From the returning signal of four receivers surrounding the emitter, the time-averaged velocities and velocity fluctuations in the three directions (v_s, v_n and v_z) are derived. The ADVP has the major advantage of measuring entire profiles at one go. Because the flow in the upper 0,02 m of the water column is perturbed by the ADVP, the velocities in this layer were extrapolated by means of procedures outlined by Blanckaert and Graf (2001). For a more detailed description of the ADVP, see Lemmin and Rolland (1997) or Blanckaert and Lemmin (2006).

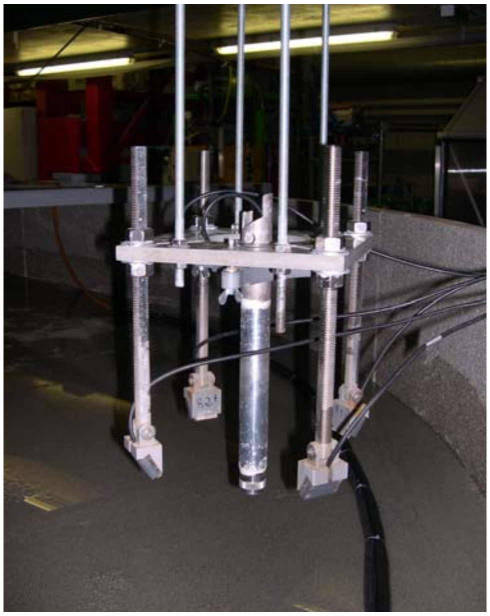


Figure 3. Acoustic Doppler Velocity Profiler (ADVP)

3 EXPERIMENTAL RESULTS

In general, the flow in river bends is decomposed along the reference axes. The decomposition results in a cross-flow, $U_n = \langle v_n \rangle$ that represents the translatory motion, and the two components (v_n^*, v_z) which represents the circulatory motion, see Bradshaw (1987):

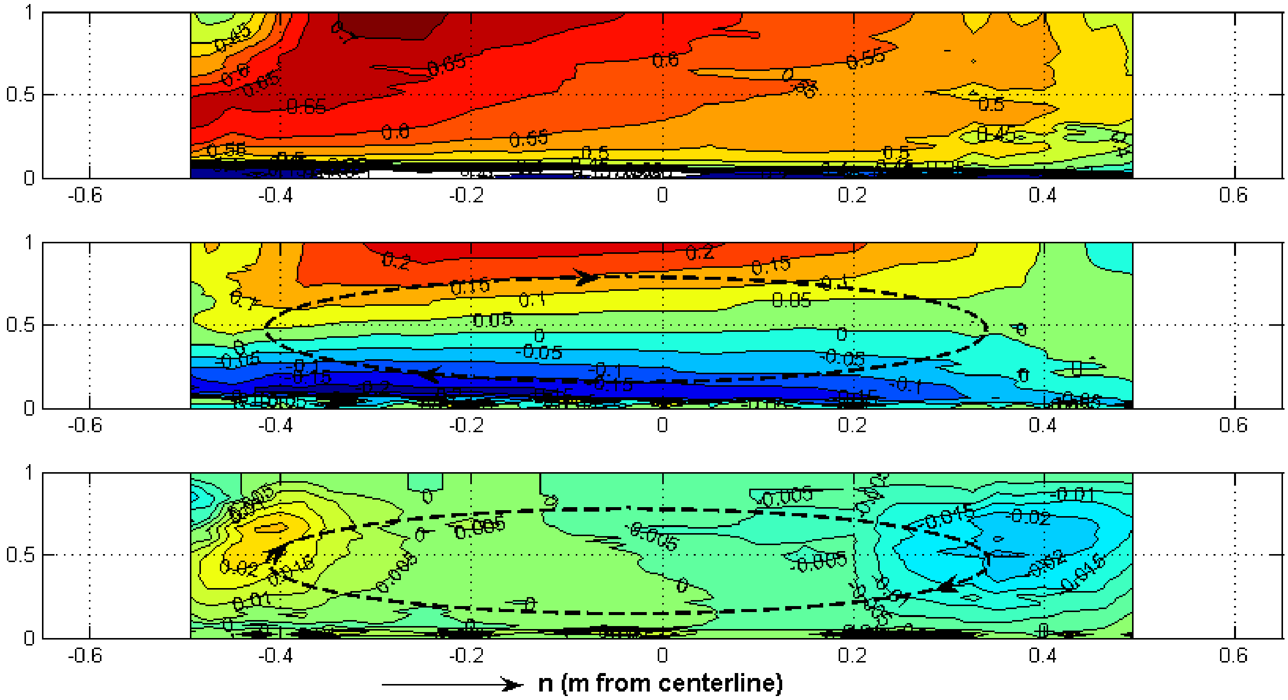


Figure 4: v_s, v_n and v_z in cross-section at 90° for the situation without bubbles. z/h=1 at the water surface and z/h=0 at the bed.

$$\begin{cases} v_s = U_s + v_s^* \\ v_n = U_n + v_n^* \\ v_z \end{cases} \tag{1}$$

To illustrate the effect of a bubble induced circulation on the flow, the three-dimensional velocity distributions in the cross-section at 90° are shown for the flow without and with bubble screen Figures 4 and 5, .and depth-averaged flow quantities are shown in Figures 6 and 7.

In Figure 4, where the flow velocities for the reference situation without bubbles are given, the circulatory motion is indicated for the main curvature induced circulation cell. Maximum transversal and vertical velocities are about $v_n = \pm\ 0.2\ \mathrm{ms}^{-1}$ and $v_z = \pm\ 0.025\ \mathrm{ms}^{-1}$, respectively. The inclination of the isolines of v_s are illustrative of advective momentum transport by this secondary circulation. Figure 6 shows that the secondary circulation develops at the bend entry, reaches its maximum at approximately 90$^{\mathrm{o}}$ in the bend and weakens further downstream.

In Figure 5 the flow velocities are given for the same hydraulic conditions and in the same cross section but now with the bubble screen in operation. In the cross section between n= -0.5 and n= 0.4 two circulation cells can be observed, the curvature induced circulation, smaller in size, more or less equal in strength and direction of rotation and the bubble induced circulation, covering roughly half of the flume width and with a rotation opposite of the curvature induced circulation. The bubble induced circulation is only slightly weaker than the curvature induced one. The vertical downstream velocity at the junction of both cells is amplified and reaches maximum values of about $v_z = -0.055\ \mathrm{ms}^{-1}$.

The secondary circulation pattern is well visualized by means of the functional ψ, defined as:

$$\psi = \frac{1}{2}\left(\psi_n + \psi_z\right)$$

$$\psi_n = -\left(1 + n/R\right)\int_{z_b}^{z} v_n^* dz$$

$$\psi_z = \int_{-B/2}^{B/2}\left(1 + n/R\right) v_z dn - \langle\langle \psi_z \rangle\rangle + \langle\langle \psi_n \rangle\rangle \tag{3}$$

The factor (1+n/R) accounts for the divergence of the transversal coordinate axis. $\langle\langle \psi_n \rangle\rangle$ and $\langle\langle \psi_z \rangle\rangle$ represent the grid-averaged value of ψ_n and ψ_z, respectively.

In fully-developed curved flow ($\partial/\partial s$=0, infinite bend), ψ_n=ψ_z and ψ represents the classical definition of the streamfunction (Batchelor 1967), whence the functional ψ will be called pseudo-streamfunction hereafter.

This pseudo-streamfunction has the advantage of being a scalar quantity, contrary to the secondary circulation vector $\left(v_n^*, v_z\right)$. Patterns of secondary circulation measured in the same experimental set-up have been presented by Blanckaert (2002b) by means of a similar pseudo-streamfunction.

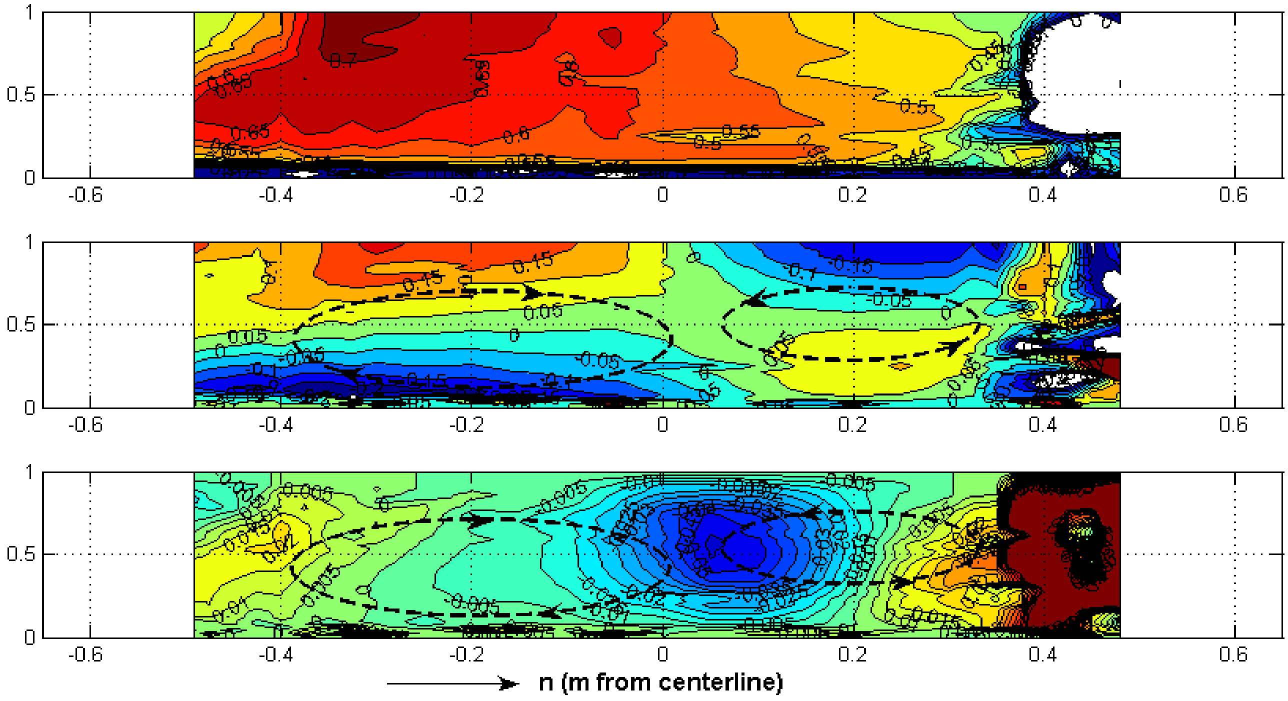


Figure 5: v_s, v_n and v_z in cross-section at 90° for the situation with bubble screen. z/h=1 at the water surface and z/h=0 at the bed. Close to the bubble screen at n=0.45 m, flow velocity could not be measured accurately.

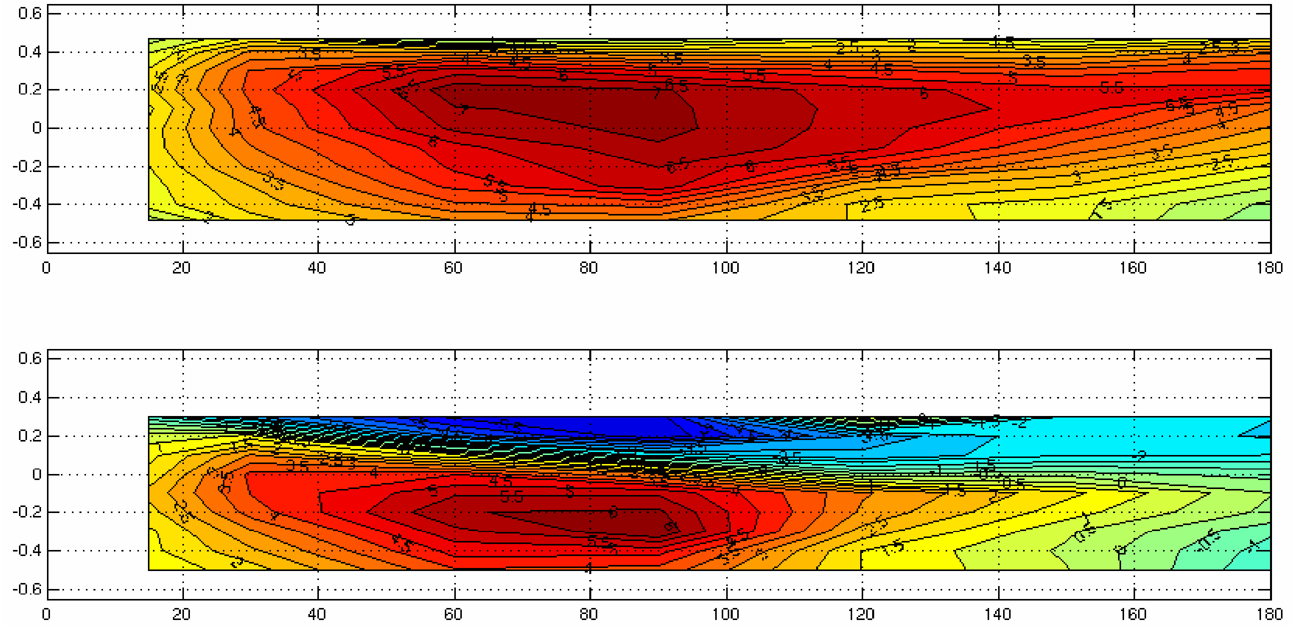


Figure 6: Distribution of the secondary normalized depth-averaged secondary circulation strength $100\langle\psi\rangle/(UH)$ in the bend, (a) Reference situation without bubble screen. (b) With bubble screen. Horizontal axis angle in the bend reach, vertical axis *z/h*.

Figure 6 shows the strength of the secondary circulation parameterized by the normalized depth-averaged pseudo-streamfunction, $100\langle\psi\rangle/(UH)$, for the curvature induced circulation only and for the curvature induced circulation in combination with the bubble induced circulation. The bubble induced circulation pushes the curvature induced circulation towards the inner bend and reduces its transversal extent, but has hardly any influence on its strength.

Figure 7 shows the distribution of the normalized downstream bed shear stress component, τ_{bs}/τ_b, estimated with a Chézy type relation ($\tau_b = C_f\ U_s^2$). Without a bubble induced circulation cell the core of the curvature induced bed shear stress starts at the upstream side at the inner bend and gradually shifts to the outer bend, which is reached at the bend exit. With a bubble induced circulation cell the core of the bed shear stress does not migrate further than the junction of both circulation cells, which is found near the centreline of the flume. The bed shear stress decreases towards both banks.

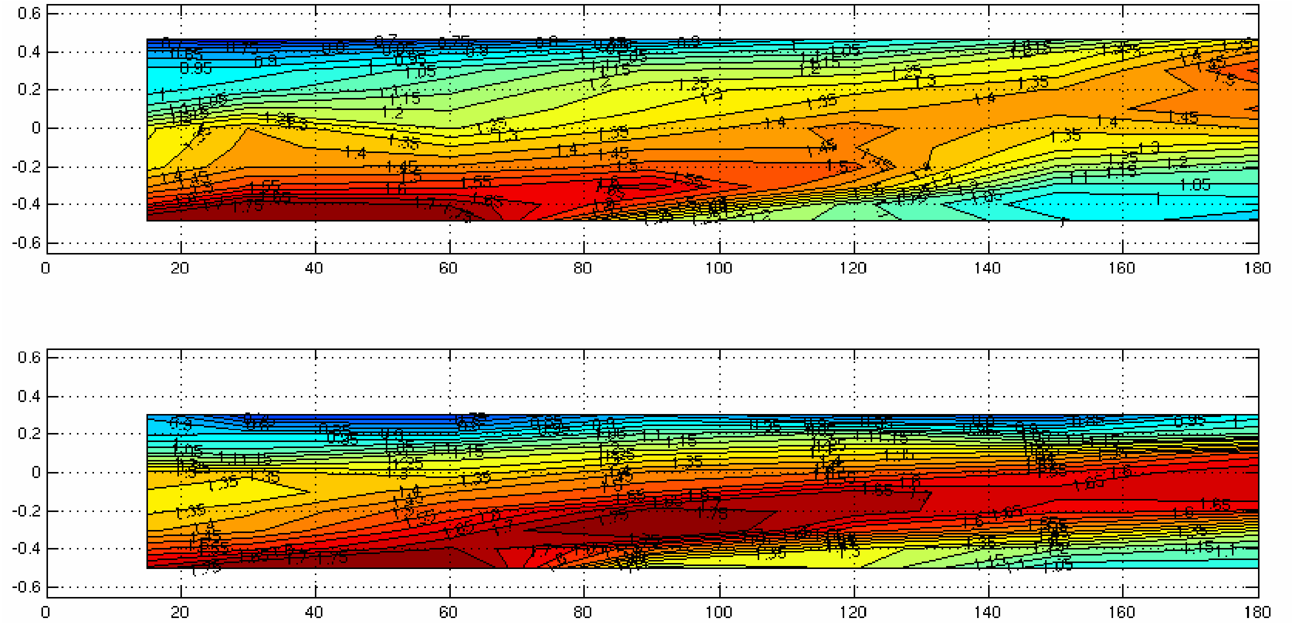


Figure 7: Distribution of the normalized downstream bed shear stress, τ_{bs}/τ_b, in the bend, (a) Reference situation without bubble screen. (b) With bubble screen. Horizontal axis angle in the bend reach, vertical axis *z/h*.

4 DISCUSSION

The experiments in the strongly curved flume with fixed flat bed show that a bubble induced circulation cell is able to reduce the size of the curvature induced circulation cell.

In case of an alluvial erodible bed, the curvature induced circulation cell transports the sediment from the outer bend to the inner bend due to the direction of the flow at the river bed. For equilibrium condition the drag force of the flow in *n*-direction balances the gravitational force in the same direction. It is expected that, in case of a combination of curvature induced and bubble induced circulation cells, the thalweg will follow the line through the downward junction of both cells and that the cross sectional bed level gradient will be roughly zero along this line. Because of the decrease in size of the curvature induced circulation cell the position of the thalweg will be closer to the centreline. The circulation strength of the curvature induced cell is hardly reduced, so the cross sectional bed slope at the inner bend will be approximately equal to the slope without bubble induced circulation. Due to the shift in thalweg one may nevertheless expect an increase in navigational width, see Figure 8.

The resulting bed-level might show a decrease in the amplitude of the point bars. Whether point bars are still present in the situation with a bubble induced circulation cell is something that must be shown through further research.

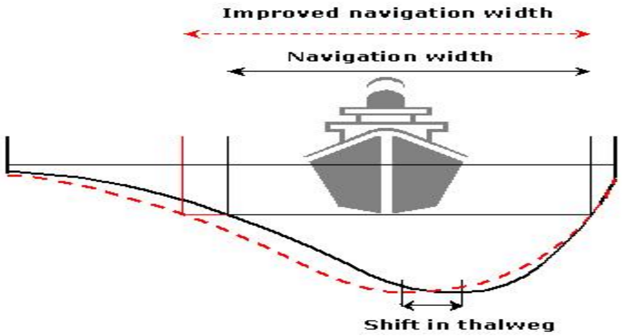


Figure 8: Possible improvement in width of navigation in case of curvature induced and bubble induced circulation cells.

The main advantage of a bubble screen compared to other techniques, which try to avoid the existence of point bars, is its reversibility. Whenever the compression stops, the bubbles are no longer present, and the flow pattern goes back to normal. In periods of low discharge (and little morphological activity), there is no need for the bubble screen to be present. Only when sediment redistribution is likely to cause problems (this is typically during high discharges) the bubble screen needs to be activated. As a nice side-effect, it may also have an additional positive effect on the ecology in the river. Existing techniques like bottom vanes or fixed layers are always present, and hence do also have an effect at low discharges. This effect is not always appreciated.

Before applying this technique in practice, further research is needed with respect to technical and economical aspects. The principal seems to work in a flume, but is it also applicable in a real river? The width-to-depth ratio of the flume was about 8.3, while a real river like the Waal has typically width-to-depth ratios over 50. Not only is there a question with respect to the mechanism (will there also appear two cells) but there is also the technical question with respect to the generation of bubbles (which obviously must be an order of magnitude larger than in the experiment) and the energy needed for that.

5 CONCLUSION

Preliminary experiments in a strongly curved flume convincingly show that a bubble screen reduces the width extent of the curvature induced circulation cell.

A bubble induced circulation cell develops that is roughly similar in strength, but smaller in spanwise extent. It exists next to the counter rotating curvature induced circulation cell, which is shifted in inward direction but hardly reduced in strength. The core of maximum downstream velocities is shifted from near the outer bank in inward direction to the junction of both circulation cells. Over a mobile bed, this would result in a more uniform depth distribution with a maximum depth at the junction of both circulation cells.

Before applying this technique in real life situations however, further technical questions need to be resolved, such as:

- During which period of time or during which flow conditions is a bubble screen most effective to increase the width for navigation?
- How much energy is required for such a period?
- Would the navigation be hampered by a bubble screen?
- Will there be an increase in bank erosion at the outer bank?

Besides demonstrating the potential of the bubble screen technique, the measurements provide detailed data on the 3D flow field in open-channel bends, which can be useful for validation of numerical models.

6 REFERENCES

Baptist, M. (2005): “Modelling floodplain bio geomorphology.” Thesis Delft University.

Batchelor, G.K. (1967). “An introduction to fluid dynamics“. Cambridge University Press.

Blanckaert, K. (2002a): “Flow and turbulence in sharp open-channel bends.” PhD-thesis Nr 2545, Ecole Polytechnique Fédérale de Lausanne, Switzerland. (see "ftp: //lrhmac15.,epfl.ch/Pub/ Thesis/Blanckaert/PhD").

Blanckaert K. (2002b). “Secondary currents measured in sharp open-channel bends.” Proc. River Flow 2002, Louvain, Belgium.

Blanckaert, K. & de Vriend, H. J. (2003). “Non-linear modeling of mean flow redistribution in curved open channels.” Water Resources Res., AGU, 39(12), 1375. (doi:10.1029/2003WR002068)

Blanckaert, K., and de Vriend, H. J. (2004). “Secondary flow in sharp open-channel bends.” J. Fluid Mech, Vol. 498, 353-380. (doi:10.1017/S0022112003006979).

Blanckaert, K. & Graf, W. H. (2001). “Experiments on flow in an open-channel bend. Mean flow and turbulence.” J. Hydr. Engng, ASCE, 127(10), 835-847.

Blanckaert, K. & Lemmin, U. (2006). “Means of noise reduction in acoustic turbulence measurements.” J. Hydr. Res., IAHR., 44(1), 3-17.

Bradshaw, P. (1987). “Turbulent secondary flows.” Annual Review Fluid Mechanics, 53-74.

de Vriend, H.J. (1981): "Velocity redistribution in curved rectangular channels“. J. Fluid Mech., Cambridge Univ. Press, 107, 423-439.

de Vriend, H.J. (1999): “Long-term morpho dynamics of alluvial rivers and coasts.” In. G. Bianchi (Ed.), Environmental applications of mechanics and computer science (p. 1-19). CISM Courses and Lectures. No. 409, Springer Wine New York.

Fargue L (1868). “Etude sur la corrélation entre la configuration du lit et la profondeur d'eau dans les rivières à fond mobile”. Annales des Ponts et Chaussées.

Hossain, M.M., Rahman, K.M., Ferdousi, S., Islam, M.Z. and Mosselman, E. ,2005, "Bottom vanes to mitigate erosion hazard in medium sized rivers of Bangladesh", Proceedings of International Conference on Disaster Management Achievements and Challenges, 18-20 November 2005, Nepal.

Jongeling, T.H.G., and Flokstra, C, "Bodemschermen. Stromingskrachten en snelheidsveld bij variatie van de schermhoogte.” (In Dutch). Delft Cluster Report, the Netherlands, 2001.

Lemmin, U. & Rolland, T. (1997). “Acoustic velocity profiler for laboratory and field studies.” J. Hydr. Engng, ASCE, 123(12), 1089-1098.

Odgaard, A.J. (1981). “Transverse bed slope in alluvial channel bends.” J. hydr. Div., ASCE, 107(HY12), 1677-1693.

Rozovskii, I.L. (1957): “Flow of Water in Bends of Open channels.” Acad. Of Sciences of the Ukrainian S.S.R., Inst. Of Hydrology and Hydraulic Eng. Kiev.

Schielen, R.M.J., Doelman, A and De Swart, H.E. (1993): “On the non-linear dynamics of free bars in straight channels.” J. of Fluid Mech. 252: 325-356

Seminara, G. (1995): “Invitation to river morpho dynamics.” In A. Doelman and A. van Harten (eds.) Non-linear dynamics and pattern formation in the natural environment (p. 269-294), Pitman Research Notes in Mathematics (335), Longman, Essex.

van Bendegom, L. (1947): “Enige beschouwingen over riviermorfologie en rivierverbeteringen.” (in Dutch). De Ingenieur, 59, 4, B&W. pp. B1-B12. (“Some considerations on river morphology and river training.”)