Helical cell motions in a small ice-covered meander reach

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Exploration of the flow field with a Pulse-Coherent Acoustic Doppler Profiler gives new high resolution observations of the secondary flow pattern occurring in a natural ice-covered meander reach. Surveys were conducted during two successive winter periods with different ice conditions. Results show clear evidence of two stacked counter rotating helical cell pattern occurring at the entrance of the bend. The pattern rapidly evolves downstream, possibly reducing to one helical cell rotating in an opposite direction than one expected in open channel flows. Surprisingly coherent flow pattern rapidly forms at the exit of massive frazil ice obstruction in the bend. Thus, frazil ice is shown to have a non-persistent impact on secondary flow pattern and helical cells to be resilient features of the flow pattern in river bends.
1. Introduction

Flow structure in meander bends has been extensively studied both in flume (Blanckaert and Graf, 2001) and field experiments (Frothingham and Rhoads, 2003). Flow structure in meander bends is affected by centrifugal acceleration and is highly three-dimensional. Despite this high complexity, persistent rotating features have been detected in the flow field. Surface waters deflected by centrifugal acceleration are directed toward the outer bend. Raising of flow occurs at the outer bed with a transverse slope that acts to redirect flow near the bed and toward the inner bend. This twofold mechanism forms a rotating motion progressing downstream that can be grossly represented as a helical pattern. This feature is coincident with high shear stress directed at the outer bend and defines the passing route of sediment transport. The flow field is thus connected with the erosion and deposition pattern at the meander reach scale that defines the shape and evolution of river morphology.

In comparison, knowledge concerning the flow structure in ice-covered meander bends is contrastingly slim. Ice-covered flow in river bends has attracted some attention in the late eighties in the perspective of studying the displacement of floating ice and the occurrence of ice jams in meanders. Urroz (1988) and Zufelt (1988) have both studied the flow field in flumes reproducing highly curved river bends. By investigating the lateral components of velocity profiles, the authors have found evidence of two stacked counter rotating helical cell motions. Urroz and Ettema (1994) have found that this pattern can be partly described by the two layer hypothesis, which describes the flow structure as two open channel boundary layers developed in the opposite direction and stacked on top of each other.

The occurrence of two helical cells in natural ice covered meander reaches has yet to be observed. Natural settings are expected to offer more complexity because of irregularity in flow depth and ice cover thickness. Velocity measurements are needed to feed models describing ice-covered river flow structure, but also to assess the ubiquity of the helical flow model in different natural settings and ice conditions. However, the lack of adequate instruments has long impeded this type of survey. The Pulse-Coherent Acoustic Doppler Profiler (PC-ADP) is a relatively new instrument for field surveys that can measure entire velocity profiles simultaneously in the three components of the flow. This capacity offers the opportunity to sound a vast volume of flow with good spatial and temporal resolution. In this study, surveys have been conducted in two successive winter periods in a small meandering reach. The surveys has allowed us to 1) evaluate the potential of the instrument to measure velocity in a complex flow field in an ice-covered river reach; 2) to detect the presence of helical cells and 3) to assess the variability of the flow structure during two successive winter conditions. The occurrence of massive frazil ice accumulations in the river bend during the first survey gave us an insight of the sensitivity of helical cell motions to increased roughness.

2. Methodology

Field surveys were conducted in early March 2007 and 2008 at a small meandering reach of the Neigette River, which is part of the catchment of the Mitis River (Quebec, Canada). The meander reach is deeply incised and stabilized by compact clay deposits. Bed material is composed of sand and discontinuous ripples were locally observed on the bed at the head of the
pool. The radius of curvature is low (~50 m) and results in a sharp 134° change in talweg orientation (figure 1b). Discharge was estimated at 1.7 m³/s (~3% of bankfull discharge) in 2007 and at 2.2 m³/s (~4%) in 2008. The ice cover thickness was measured and undercover irregularity was visually inspected using a submersible optical camera. Roughness was classified in three discrete classes judging from the overall variability in the reach: smooth, smooth-rough and rough (see figure 2 for an illustration of each category). Thirty eight velocity profiles positioned along 16 transects were measured during a two day field work. Sampling design was chosen to cover with a higher density of profiles the apex of the meander where helical cells were thought to be more likely to appear. Sampling design is summarized in figure 1b. Profiles are identified by their relative position along a particular cross-section measured from the outer bend.

Velocity profiles were collected using a Sontek 1.5Mhz Pulse Coherent Acoustic Doppler Profiler (PC-ADP). This instrument has the ability to simultaneously collect entire velocity profiles in all three components of flow (longitudinal, lateral and vertical). The PC-ADP relies on a particular measurement technique, the coherent mode, which allows to reach a vertical resolution on the order of few centimeters. The instrument sends two short sound impulses in the water column where it is backscattered by the buoyant particles in movement within the water. The difference of phase between the two signals is measured and allows for a rapid estimation of flow velocities. Velocities are measured parallel to three radial beams inclined at 15° with the axis of the instrument, forming a sampling volume extending outward in the water in the shape of a cone (figure 1a). The instrument measures velocities at several depths of flow which corresponds to slices, named cells, of the cone. Velocities are afterwards converted into a cartesian framework which postulates that the flow measured by all beams is equivalent, i.e. flow is meant to be homogeneous in the sampling volume. We used a tripod mount with a scaled rod which allowed us to insert the instrument head even with the ice undercover. Blanking distance, the no see area near the nose of the instrument, was set to its minimum length of 0.05 m and cells length varied between 0.044 or 0.105 m. Velocities sampled are averaged at a frequency of 1 Hz for 10 minutes long time series. Data series were first inspected to discard low quality data (for details, see Lacy and Sherwood, 2004). Time series were averaged and rotated to allow the analysis of lateral components of velocity. The rotation used herein is applied to every profile of one cross section to give a net zero lateral discharge (Markham and Thorne, 1992a,b).

3. Ice cover and velocity profiles

Figure 2 illustrates the spatial variability of ice cover thickness and roughness classes for both 2007 and 2008 surveys. Ice thickness at the reach scale ranges from 51 to 76 cm and from 53 to 69 cm for the 2007 and 2008 surveys, respectively. Despite range similarity, the first survey presents more scatter both in range and in spatial organisation. Ice thickness is more patchy and presents more drastic local changes in 2007. Values measured at the same sites between the two surveys are thus statistically different (R = 0.19, p = 0.28). Nonetheless, both surveys appear to follow a trend that matches the river depth with thicker ice in the pool than in riffles areas. The correlation coefficient between ice thickness and flow depth is significant for the 2007 survey (R = 0.38, p = 0.024), but is not for the 2008 survey (R = 0.13, p = 0.44). The scatter in the values of the 2007 survey is also associated with ice undercover roughness. The rough category represents 48 % of observed sites in 2007 as opposed to 16% for the 2008 survey. A chi-square test shows the distribution of values to be significantly different between the two year of observations.
(χ² = 6.9, p = 0.03). Also, at the time of measurement of the 2007 survey, the pool area was full with frazil ice particles that often hindered the assessment of the undercover state as well as the measurement of velocity profiles. This volume of particles acts as a porous roughness that can modify the pattern of flow in the meander.

Figure 3 presents two velocity profiles collected during each survey at the entrance edge of the pool where flow is still unaffected by centrifugal acceleration. The two surveys show differences in flow depth and velocities due to the different discharge, but all profiles entering the bend presents a classical parabolic shape typical of under ice flow. Also, the ice undercover is rougher at the entrance of the bend for the 2007 survey. As such, profile at position 8°-1/2 (2007) has an asymmetrical shape where maximum velocities are found closer to the bed. Undercover roughness may shift the maximum velocities plane to change the position of flow divergence and flow redirection toward the inner bend. Thus, helical cell motions are the result of the joint factors of centrifugal acceleration and ice roughness conditions.

4. Secondary flow pattern

Figure 4 illustrates flow velocities along five cross-sections (30° to 105°) near the apex of the meander for the 2008 survey. From bottom to top, the cross-sections show the downstream evolution of secondary flow patterns where color and vector represent respectively the downstream (u) and joint lateral(v) and vertical(w) average velocity components of flow. For an easier lecture, a schematic view of the orientation of the vectors is shown on the right side of the figure. Downstream maximal average velocities follow closely the outer bend. The secondary component of flow is one order of magnitude smaller than the primary flow, in a proportion ranging between 5.3% and 11.2%. Helical motions appear first at the 30° cross-section where profiles in the 1/3 and 1/2 positions show a clear mid-depth deflection toward the outer bend as well as two inward motions near both ice and bed wall. This flow pattern is representative of two superimposed helical cells. Past this cross-section, the flow field is less coherent. Profile at the position 1/3 on the 51° cross-section also conforms to a helical cell pattern, although the lateral extent of it remains unknown. Profiles along the 65° and 88° cross-sections still show a mid-profile deflection in the outward direction while near ice flow remains directed toward the inner bend. However, near bed secondary flows are not apparent. Profile at the position 1/3 of the 65° cross-section suggests a potential inward flow near the bed, although this interpretation is tentative due to the lack of information. Profiles along the 88° and 105° cross-sections present mid-depth and near-bed flow directed toward the outer bend while near-ice flow is directed toward the inner bend. This pattern suggests the presence of only one helical cell rotating in a counter clockwise direction. Secondary flows past the 105° cross-section show no apparent coherent pattern.

During the 2007 survey, frazil ice particles obtruded a large volume of the bend, thus no velocities have been measured in the pool area. However, the PC-ADP allowed us to assess indirectly the thickness of frazil ice accumulation by analyzing the strength of the backscattered signal. Strong rebound clearly identified area of frazil ice accumulation. Figure 5 is a representation of frazil ice obstruction and flow velocities along the 65°, 88° and 105° cross-sections of the 2007 survey. Frazil ice is shown to be mainly confined toward the inner bend or near the talweg. Velocities measured at the exit of bend (105° cross-section) show a surprisingly
coherent motion despite the upstream obstruction caused by the presence of frazil ice. Profiles show two near bed and ice inward motions suggesting the presence of two helical cells. Profile at position 1/2, at the innermost edge of the bend, shows a closed rotation cell which suggests that the two helical pattern is limited to the outer half of the bend.

5. Discussion

These results show that two stacked helical cell motions are present in the river bend under an ice cover. However, data from the 2008 survey does not reveal a clear downstream continuous pattern of the helical cells. Two different possibilities emerge from the above. Firstly, the two helical cells pattern observed at the entrance of bend is continuous downstream. Near-bed inward secondary flows would be present, but is not apparent because of the lack of information in the last cells of the measured profiles near the bed. Secondly, the two helical cells become one cell rotating in an opposite direction when compared to ice-free flow conditions.

The first possibility pertains to the capacity of the PC-ADP to measure complex three-dimensional flow field. In fact, the postulate of flow homogeneity in the sampling volume appears somehow limiting if one is interested in complex flow fields typical of small river meander reaches, since the sampling volume grows with distance \(d\) from the instrument \((\sim0.5d)\). Flow homogeneity near the ice is thus less constraining than near the bed where a large sampling volume intermingles with a complex flow field, bed irregularity and high turbulence intensities. Thus, small river bends do not appear as an environment where the PC-ADP can be put to its best use. Still, if one accepts the hypothesis that two helical cells are present, then the two helical cell motions are spatially limited. Helicity is observed between the 30° to the 88° cross-sections, rapidly decaying thereafter. Finally, traces of the two helical cells are confined to the outer half bend, a result that is similar to what has been reported in open channel flows (Frothingham and Rhoads, 2003).

The second possibility allows that the two helical cells do occur, but interact and transform into a single cell, which is represented by a helical rotation occurring in an opposite direction than the one expected in open channel flows. Urroz and Ettema (1994) state that the two helical cells are not independent features, but rather that they interact and become more complex. This limits the capacity to describe the phenomenon accurately with the classical two layer hypothesis. High complexity is synonymous of a weaker overall coherency that may feature several competing vorticity elements. Local higher momentum might favour one or the other cell that will grow to the expense of the other and modify the initial pattern of flow. Bank and bed morphology along with ice roughness conditions could be influential factors in determining the direction of change in cell structure. On the other hand, the 2007 survey shows the two helical cell pattern to be highly resilient. The observations have shown the presence of two counter rotating helical cells at the exit of the pool, albeit significantly obstructed by frazil ice particles. This suggests that frazil ice may not have a persistent impact on flow structure. Throughout the bend, the flow pattern is most likely affected by centrifugal acceleration while being simultaneously spatially directed to frazil free areas. Moreover, constriction most likely speeds up flow velocities, enhancing centrifugal effect and helical cell formation. A flow pattern recovering from this containment might also be more complex because of the likelihood of a recirculation area near the inner bend created by the frazil obstruction. With more closely spaced cross-sections, it
might be possible to better capture the transition between these areas and specify the effects of containment on the pattern of flow.

6. Conclusion

Exploration with a PC-ADP of the velocity field in a small meandering river reach covered with ice has led to new observations on the pattern of secondary flows in curved channels. Results show evidence of two stacked counter-rotating helical cell motions occurring at the entrance of the bend. This pattern evolves rapidly downstream, possibly transforming to one helical cell feature rotating in an opposite direction than the one expected in open channel flows. Frazil ice accumulation in the bend is shown to be a non-persistent obstacle to the development of these helical cell features. Further studies should consider increasing the density of the velocity profiles and diversifying the sites of observation to analyse flow pattern consistency over different flow and ice conditions. A larger spatial extent, covering multiple successive bends, should also be considered in order to achieve a broader understanding of the flow structure of meandering rivers under ice.

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References

Figure 1: a) PC-ADP sampling scheme; b) Meander reach sampling scheme.
Figure 2: Ice cover thickness and undercover roughness for the 2007 and 2008 surveys.

Figure 3: Velocity profiles at the entrance of pool for the 2007 and 2008 surveys.
Figure 4: Longitudinal (colored contours) and secondary flow patterns (vectors) viewed downstream from bottom to top. Right handed schemes are a synthesis of results for a better reading.
Figure 5: Frazil ice obstruction and flow velocities in the pool area of the 2007 survey.