TIDAL MEANDERS AND TIDAL DELTAS: LABORATORY OBSERVATIONS

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ABSTRACT

This paper describes a controlled laboratory experiment on the long term morphodynamic evolution of a tidal meandering channel connected to a tidal basin. The channel consisted of five meandering reaches with a sine generated shape and constant width (0.4 m). The channel was closed at one end and connected at the other end with a basin, representing the sea, where a prescribed tidal oscillation was generated. Two different experiments have been carried out, starting with different initial values of the mean flow depth.

Observations have confirmed some of the theoretical expectations, namely the development of a quasi equilibrium pattern of the average bed profile, with deep scour at the inlet and the eventual formation of a shore landward. The interpretation of the observed characteristics of the bar-pool pattern, i.e. of the sequence of scour and deposition regions forced by channel curvature, is less straightforward. In fact, bars turned out to be in phase with curvature only in the inner portion of the channel, while the seaward pattern exhibited deposition at the outer bends and scour at the inner bends.

The present experiments were also able to reproduce the formation of an ebb-tidal delta in the basin. We have performed detailed PIV measurements of the flow field over the ebb-tidal delta in the final stage of the experiment. Results show the highly asymmetric nature of the flow field, namely a quasi – irrotational character of the inflow during the flood phase and the formation of an ebb turbulent shallow jet, which is enhanced by two recirculation cells.

Keywords: tide, meanders, scours, deposition, point bars, shallow jets, ebb-tidal delta

1 INTRODUCTION

Tidal channels in estuaries and lagoons often display a meandering pattern. The problem of the possible existence of an equilibrium configuration of the bed profile of tidal channels has been the subject of theoretical investigations by Schuttelaars and De Swart (1996, 2000) and by Lanzoni and Seminara (2002). Controlled laboratory experiments have been carried out by Tambroni et al. (2005). The latter authors have shown that straight and weakly convergent tidal channels closed at one end, do indeed evolve towards an equilibrium configuration, slightly concave seaward and convex landward, in accordance with the theoretical predictions of Lanzoni and Seminara (2002).

The channel curvature modifies the lateral structure of bed topography significantly. Tidal meanders display some similarities with river meanders (Marani et al., 2002), in particular they exhibit the formation of deposition (point bars) at the inner bends and scour (pools) at the outer banks. In the wide literature developed for the fluvial case, it has been clarified that these sequences of bars and pools are almost steady features, which propagate at the very slow time scale associated with the plan form evolution of the meandering pattern, migration rates being typically of the order of meters per year. Essentially, the formation of the bar-pool pattern is due to a secondary flow which affects the trajectory of sediment particles. Laboratory experiments (Colombini et al., 1992) carried out on a meandering flume subject to a stationary flow have shown that the phase lag of the bar pool pattern relative to curvature depends on the meander wavenumber and on the aspect ratio of the channel.

Solari et al. (2001) and Solari and Toffolon (2001) have recently proposed theoretical models for flow and bed topography in infinite sequences of tidal meandering channel. They found that a symmetrical tidal wave gives rise, through a transient process, to an equilibrium bar-pool pattern characterized by relatively small symmetrical spatial oscillations throughout the tidal cycle. The average equilibrium topography is characterized by amplitudes of the point bar comparable with the mean flow depth.

The aim of the present experiments is to study the transient process whereby an equilibrium bed topography is established in a meandering channel, connected with a tidal basin. In particular we focus our attention on the characteristics of the cross–sectionally averaged bed profile and on the structure of the bar-pool pattern: the finite length of the channel will be seen to give rise to spatial variations of the latter displaying interesting features. This study also describes the formation and evolution in the near inlet region of an -ebb tidal delta similar to those encountered in nature. A detailed set of measurements of the flow field in the basin at equilibrium shows the formation of a strong shallow unsteady jet during the ebb phase and of a quasi – irrotational flow during the flood phase.

Besides its obvious geomorphic interest, the practical relevance of the problem is related to the ability to predict bend scour in tidal settings and to shed further light on the mechanisms that lead to the formation of ebb – tidal deltas.

The plan of the paper is as follows. A brief description of the experimental apparatus is presented in section 2. Results concerning the morphodynamic evolution of the bed topography in the channel and in the seaward basin are discussed in sections 3 and 4. Finally, some remarks follow in the last section.

2 EXPERIMENTAL APPARATUS

Experiments were carried out on a large indoor platform above which a meandering channel was built using zincked plate. The Cartesian length of the channel was *21.3* m. Moreover the channel was *0.4* m wide, closed at one end and connected at the other end to a rectangular basin (*2.23 m* wide and *6.5 m* long) representing the sea. The flume was composed of a sequence of five meanders with intrinsic wavelength L^*_s of *4* m, connected at each end to a straight reach *1* m long. The shape of the channel axis was chosen such to follow the law $y^*(x^*) = A^* \sin(\lambda_x^* x^*)$, with an amplitude A^* of *0.35* m and a Cartesian meander wavelength ($L_x^* = 2\pi/\lambda_x^*$) taking the value *1.7 m*.

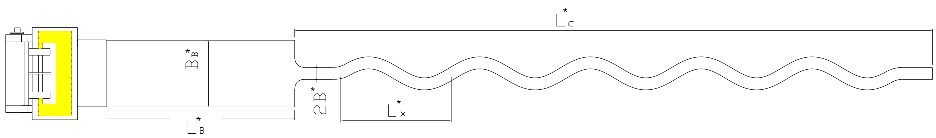

Figure 1. Sketch of the experimental apparatus and notations.

The walls of the inlet were rounded off, in order to avoid the formation of deep scour holes. The Figure 1 shows a sketch of the apparatus.

Finally, an oscillating discharge was supplied to the basin from a tank where the apparatus for tide generation was installed. The latter consisted of a cylinder set in motion by a piston held by a steel frame and controlled by an oleodynamic mechanism driven by a control system, which generated the desired law of motion. In particular, a sinusoidal tide was generated:

$$h^*(t^*) = a_0^* \sin\left(2\pi\, t^* / T\right) \qquad (2)$$

with $h^*(t^*)$ free surface oscillation in the basin, T tidal period and a^*_0 amplitude of the tidal wave.

A uniform layer of cohesionless granular material of sufficient thickness was laid on the bottom of both the flume and the basin. Sediments were chosen light enough to be entrained in suspension throughout most of the tidal cycle with the values of friction velocity typically generated in the present experiments. The final choice was to use polycarbonate grains, characterized by a density of $1.27\ t/m^3$ and median grain size $d^*_s=0.15\ mm$.

Two experiments have been carried out, changing the initial value of the mean flow depth D_0^*. Table 1 shows the values of the relevant parameters for the two experiments.

		EXP. 1	EXP. 2
Tidal period	T [s]	170	170
Mean flow depth at the channel inlet	D^*_0[m]	0.085	0.04
Tidal peak velocity at the channel inlet	U^*_{max} [m/s]	0.3	0.2
Wave amplitude at the channel inlet	a^*_0[m]	0.021	0.009

Table 1. Values of the relevant parameters relative to the initial conditions of the two experiments.

3 MORPHODYNAMIC EVOLUTION OF THE CHANNEL

3.1 BED PROFILE

Let us first briefly discuss the morphodynamic evolution of the cross – sectionally averaged bed profile. Due to the flood dominant character of the tidal wave in the initial stage (displayed by peak velocities higher during the flood phase than during the ebb phase, and high-water period shorter than low-water), a net sediment flux directed landward arises. Sediments are then eroded in the seaward portion of the channel, driven landward, and deposited in the inner reach. In particular, a fairly sharp front of the bed profile develops and migrates landward. This is consistent with the theoretical results obtained by Lanzoni and Seminara (2002) and with laboratory observations on rectilinear and weakly convergent tidal channels (Tambroni et al., 2005). The Figures 2 and 3 show the temporal evolution of the laterally averaged bed profile for run 1 and 2, respectively. Note that D^*_0 is the mean flow depth at the channel mouth at the beginning of the experiment, η^* is the local and instantaneous value of the average bed elevation and s^* is the landward oriented intrinsic coordinate measured along the channel axis, with origin located at the channel inlet.

Let us first discuss the results of the first experiment. The bed profile (Figure 2) evolves starting from an initial configuration characterized by a fairly weak upslope (10^{-3}). Since the very beginning of the experiment (say 100 cycles), a deep scour is observed at the channel mouth. Note that the scour depth at the channel inlet evolves throughout the experiment, reaching a quasi equilibrium value of the order of the initial mean flow depth after 8000 tidal cycles. The sediment front develops quite rapidly, grows and migrates landward, reaching the channel end. Proceeding with the experiment, a wet and dry region forms and the depositional area grows until the bed elevation reaches the mean water level. Note that, while the bed reached an equilibrium state in the landward portion of the channel, in the seaward reach the laterally averaged bed profile still exhibited a weak oscillatory behaviour at the end of the experiment.

The small scale oscillations displayed by the bed profile in the laboratory are associated with the presence of small-scale bed forms. Larger scale fluctuations (see the bed profile after 100 cycles) occur on the meander scale. These oscillations, particularly intense in the initial stage of the experiment (say after 100 cycles), are presumably driven by the tendency of bed topography to adapt to the spatial variations in sediment flux associated with channel curvature. In particular, the channel width being fixed, the system chooses to vary the local bed slope in order to accommodate the required sediment transport. The mechanism looks similar to that studied by Solari and Seminara (1998) for steady flow in a constant curvature channel: the deformation of the cross section displays scour at the outer bend and deposition at the inner bend, hence the Shields stress in the outer portion of the cross section is larger than in an equivalent straight channel, while the opposite occurs in the inner region. The resulting increase in sediment transport can only be balanced by a reduction of bed slope in the downstream curved reach. In our case, curvature is not constant, hence the local bed slope must experience spatial changes on the length scale of a meander.

Let us now move to the second experiment. The plot in Figure 3 refers to the equilibrium stage. As observed in the first experiment, the longitudinal bed profile is inward up-grading. It is interesting to note the presence of large – scale oscillations of the mean bed profile which, unlike in run 1, persist until the final stage. Furthermore, the fact that they are observed close to the inlet, suggests that they might arise as a bottom instability forced by the inlet boundary condition. Channel curvature may also play some role, leading to a local adaptation of bed topography as mentioned in the above paragraph. However, the lack of a systematic theory for finite length tidal channels, does not allow for a conclusive interpretation of this phenomenon.

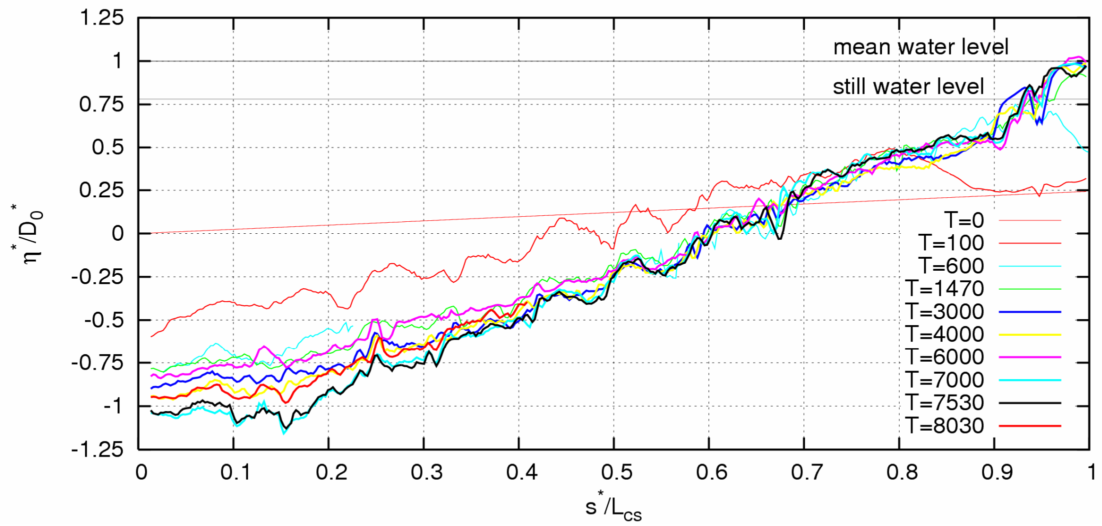

Figure 2. Temporal evolution of the laterally averaged bed profile along the channel (Experiment n° 1).

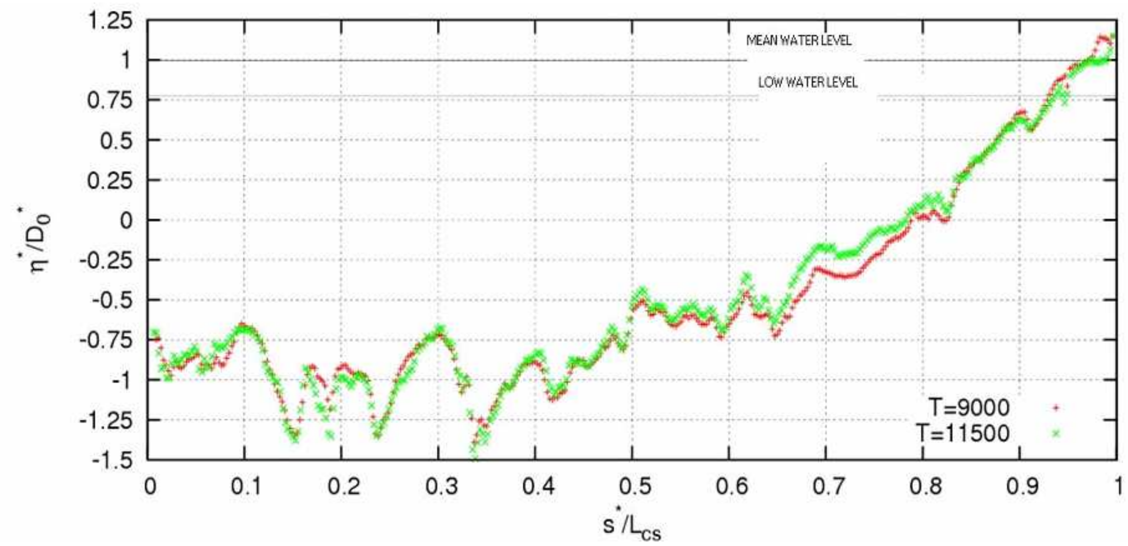

Figure 3. Final configuration of the laterally averaged bed profile along the channel (Experiment n° 2).

3.2 THE PATTERN OF POINT BARS

We now proceed to discuss the evolution of the bar-pool pattern driven by channel curvature. In the initial stage of the first experiment a phase lag between scour and curvature was observed throughout most of the channel (see Figure 4, where the bed elevation has been plotted after filtering the average profile out). After 100 tidal cycles deposition has been observed at the outer bend, especially in the seaward portion of the channel. Proceeding with the experiment, the deposits located in the outer region of the bends have been partially eroded. On the other hand, the bar-pool pattern in the landward reach of the channel appears to reach a stable configuration, with scours located at the outer bend and depositions at the inner bend. On the contrary, the seaward half of the channel displays a peculiar bar-pool pattern, with deposition bars out of phase with respect to channel curvature.

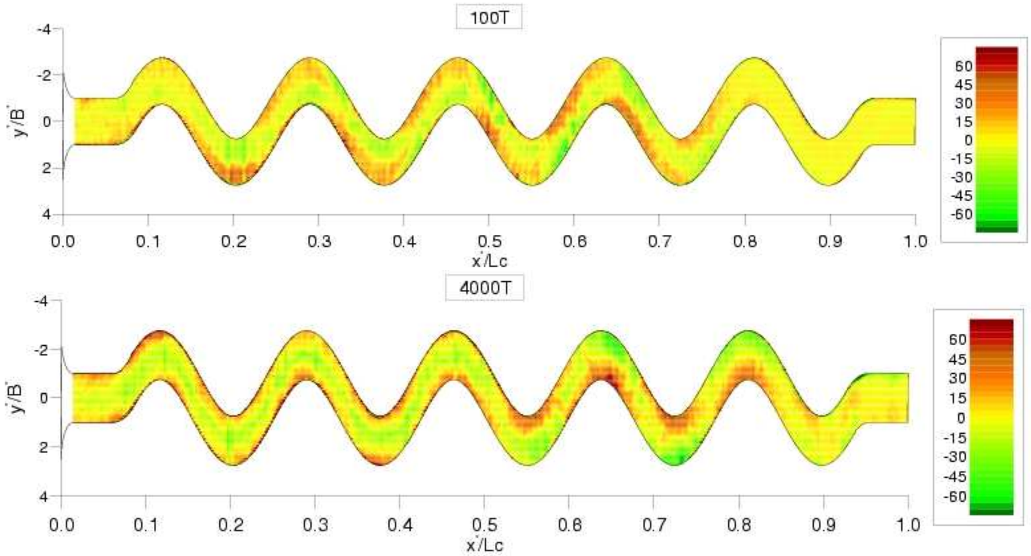

Figure 4. Evolution of bed topography showing the bar-pool pattern after 100 and 4000 tidal cycles (Experiment n° 1). Note that the laterally averaged bed profile has been subtracted. Bottom elevation is expressed in *mm*, with positive values corresponding to depositional areas.

The observed tendency of the bed topography in the seaward portion of the channel is to reach a configuration which would not be stable in nature: indeed, bank erosion would rapidly suppress curvature and the channel would recover a rectilinear pattern. This is suggestive of a strong influence of the inlet condition, which appears to force a spatial transient which delays the development of a fully developed meander pattern. In the first experiment the latter was reached in the landward portion of the channel, while in the second experiment, the whole channel was invariably covered by point bars out of phase relative to curvature (Figure 5). As pointed out above, this configuration would clearly be planimetrically unstable if the channel walls were erodible. We suggest that our observations may provide an explanation for the observation that, in nature, tidal channels are seldom curved close to their inlets (Figure 6).

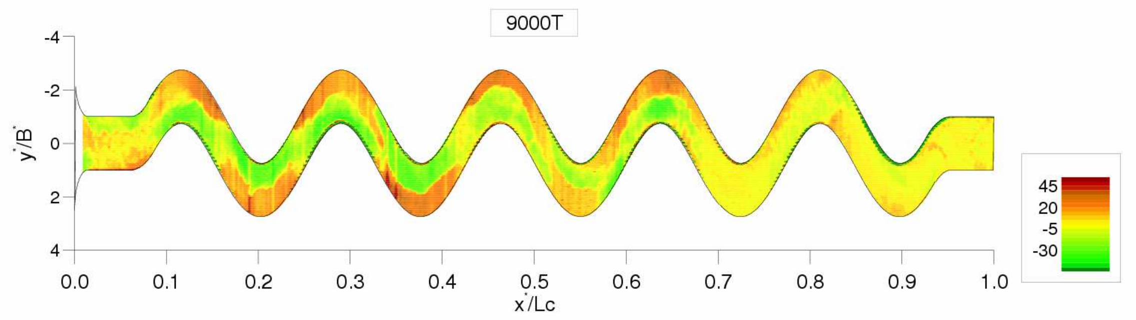

Figure 5. Map of bed topography showing the bar-pool pattern in the final stage of the second experiment . Note that the laterally averaged bed profile has been subtracted. Bottom elevation is expressed in *mm*, with positive values corresponding to depositional areas.

Figure 6. An aerial image of tidal flats and salt marshes (Skallingen, Denmark). Note that the terminal reach (towards the inlet) of tidal channels is almost rectilinear.

4 EBB – TIDAL DELTA

A significant fraction of the coastlines is bounded by confined embayments, connected to the adjacent sea/ocean through inlets interrupting sequences of barrier islands parallel to the coast (Davis, 1996). Inlets allow tidal currents to exchange water and sediments. In the area seaward of the inlet, the bathymetry is often characterized by the formation of an ebb-tidal delta, where sediments unable to re-enter the lagoon due to the asymmetric nature of the flow field, are stored. Ebb tidal deltas are located at the seaward end of the main ebb dominated channel (with peak velocities stronger during the ebb – phase) and usually flanked by two adjacent flood dominated channels. Field data extracted from the Atlantic US coast (Walton and Adams, 1976) suggest that the volume of sand stored in ebb tidal deltas is almost linearly proportional to the tidal prism, namely the volume of water that enters and leaves the lagoon during each tidal cycle. Depending on the strength of the littoral currents the ebb-tidal delta can be asymmetric with respect to the inlet orientation.

The present laboratory experiments allowed us to observe the formation of an ebb-tidal delta. From the very beginning of the first experiment (Figure 7), sediments were eroded close to the inlet, both in the channel and in the sea basin. Part of these sediments were observed to deposit in the central region of the basin. The initial width of the depositional area was approximately coincident with the channel width. Proceeding with the experiment, the extension of the ebb-tidal delta grows, both in the longitudinal and lateral directions. Scour spits are also formed in the central region of the basin: they eventually develop into a submerged channel. Along the seaward side of the barriers, i.e. along the walls of the basin adjacent to the inlet, two swash bars form, a feature typically observed in nature. The same considerations apply also to the second experiment (Figure 8). Note that the amount of sediments stored in the ebb – tidal delta is lower than in the first experiment, because of the reduction of the tidal prism.

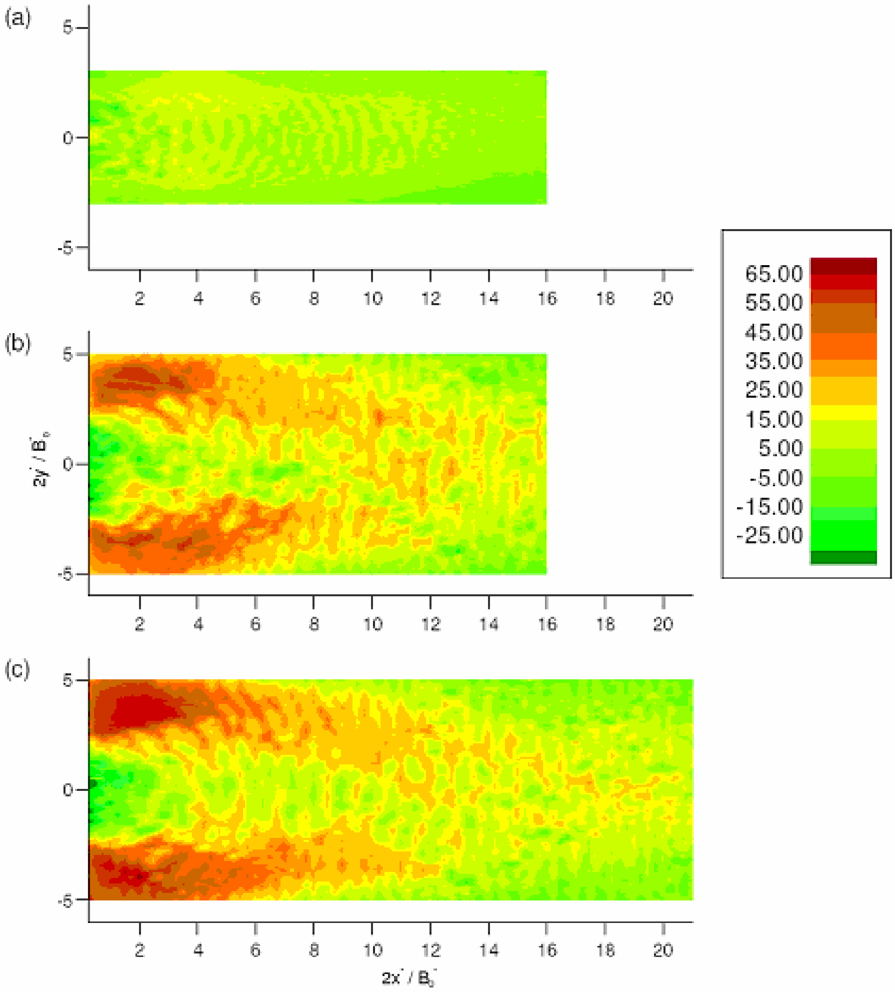

Figure 7. Evolution of the pattern of bed topography of the ebb-tidal delta measured at different times in the first experiment . (a) *t* = 100 T*. (b) *t* = 3000 T*. *t* = 6000 T*. Bottom elevation is expressed in *mm*, with positive values corresponding to depositional areas.

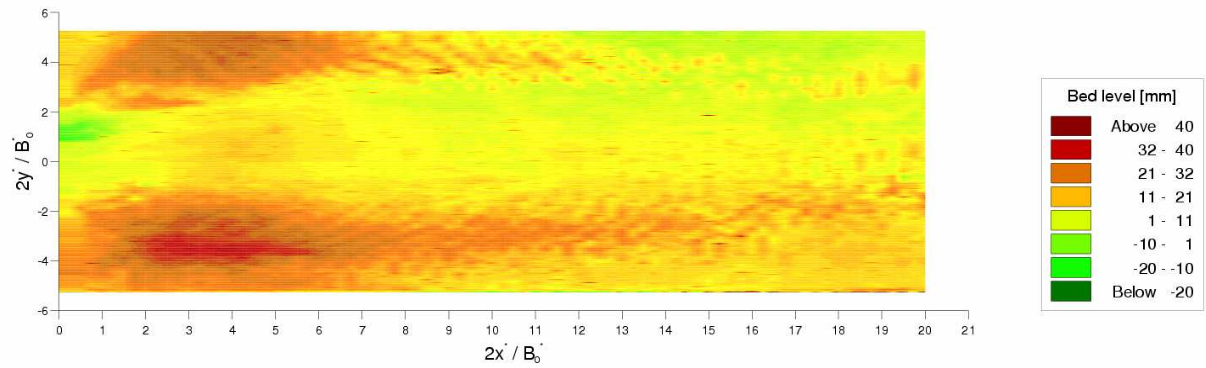

Figure 8. The final pattern of bed topography of the ebb tidal delta in the second experiment. Bottom elevation is expressed in *mm*, with positive values corresponding to depositional areas.

In order to pick up the details of the physical processes that lead to the formation of an ebb – tidal delta, we have performed a set of PIV measurements of the surface velocity in the basin in the final stage of the second experiment.

As already pointed out by various Authors (Blondeaux et al., 1982, van der Vegt et al. 2006), a strong turbulent jet is formed during the ebb – flow. The jet is responsible for the erosion of sediments in the central region of the basin. During the flood phase the flow has a radial pattern. It may be of some interest to analyze the temporal distribution of the velocity profiles at some given cross sections. Let us first focus on the inlet. The Figure 10 shows that the channel reach immediately inward to the inlet is ebb dominated, i.e. the stronger currents occur during the ebb – phase.

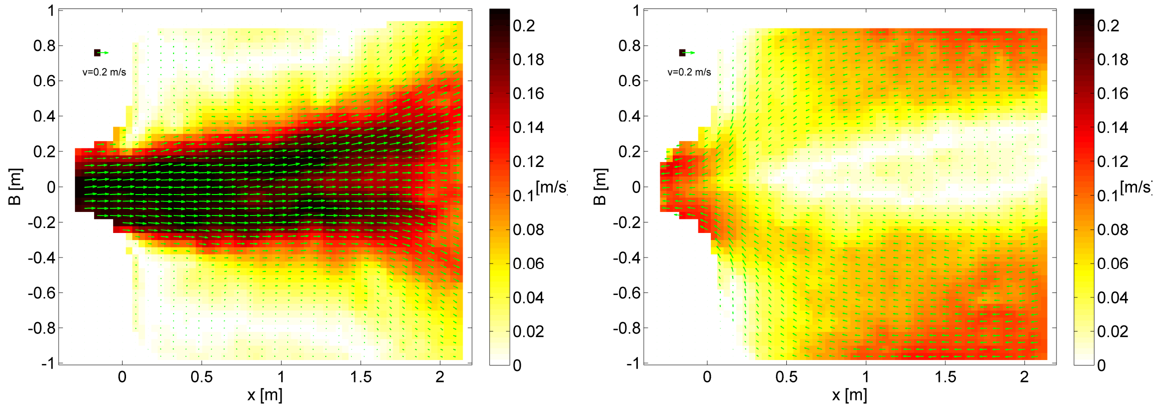

Figure 9. Surface velocity field measured in the basin at the end of the second experiment. On the left the pattern observed at some instant during the ebb phase, on the right the pattern at the beginning of the flood phase.

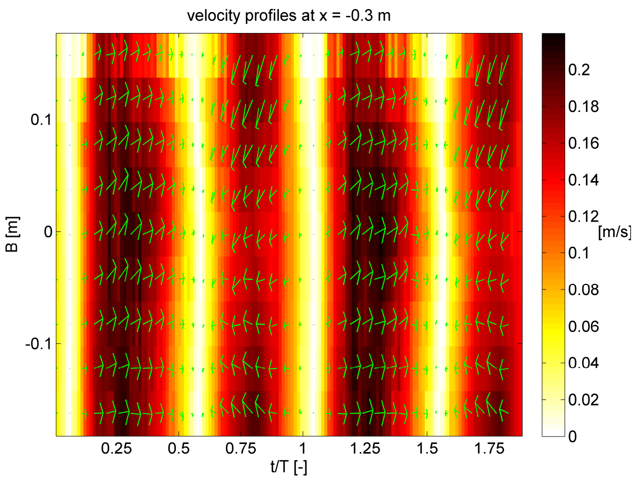

Figure 10. Temporal distribution of surface velocity measured in a sequence of two tidal cycles at a cross section located 0.3 m inward to the inlet.

If we now move to a cross section located 1 m seaward to the inlet, we can clearly distinguish a central region of the basin, which is still ebb – dominated, with strong ebb velocities associated with the jet. The portions of the basin near its sides are rather flood dominant: this is consistent with field observations which suggest that ebb tidal deltas are usually flanked by two flood dominant channels.

CONCLUSIONS

The present laboratory experiments show that a tidal meandering channel closed at one end evolves towards an asymptotic equilibrium configuration, characterized by a deep scour at the channel inlet and the formation of a shoal (a wet and dry area) in the inner reach of the channel.

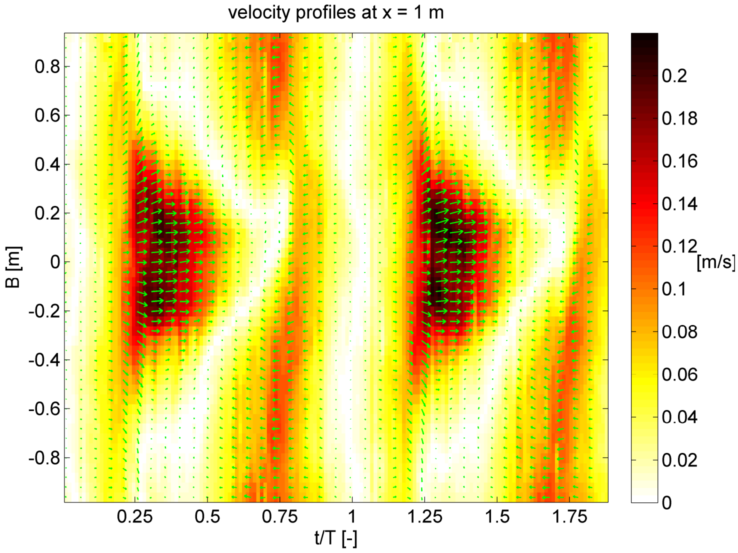

Figure 11. Temporal distribution throughout two tidal cycles of surface velocity measured at a cross section located 1 m seaward to the inlet.

The bar-pool pattern developed in the first experiment in the landward region of the channel is qualitatively consistent with field observations and with the theoretical results of Solari et al. (2001), with deposition occurring in the inner portion of the bend. However, in the seaward portion of the channel, point bars were out of phase relative to curvature, thus suggesting that the sinuous pattern in this region would be planimetrically unstable. In other words, it appears that the bed topography is strongly affected by the boundary conditions at the inlet and at the inner end. In other words, this suggests that the spatial distribution of the bar-pool pattern is not simply related to processes occurring at the meander scale: in order to capture the complete evolution of bed topography the whole channel length needs to be analyzed. This was even more evident in the second experiment, in which the bar – pool pattern was out of phase relative to curvature along the whole channel.

In the inlet region the formation of an ebb-tidal delta was observed for both the experiments. The flow field in the basin was measured in the final stage of the second experiment, showing the formation of a turbulent jet during the ebb phase and a radial quasi-irrotational pattern during the inflow.

In the near future we plan to investigate the effect of meander wavelength on the bar – pool pattern, namely the possibility that the phase – lag of bars relative to curvature may decrease as meanders get longer.

The data collected in the present experiment are also intended to provide a test case for future numerical models and theoretical analyses.

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