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Long-duration laboratory experiment of slow development of steady alternate bars

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ABSTRACT: The current view is that migrating bars are the result of morphodynamic instability in straight or mildly-sinuous alluvial channels and are therefore an inevitable feature of alluvial river beds. Steady bars, instead, require some external forcing or specific morphodynamic conditions to develop. Yet, recent numerical tests showed that steady bars may develop as a result of spontaneous morphodynamic instability, just like migrating bars, without meeting the specific conditions. We investigated this possibility in the laboratory, following the temporal evolution of alternate bars in a straight flume with mobile bed. The experiment was run with a constant discharge for about 10 weeks. Initially, the bed topography was dominated by the presence of fast growing migrating bars. After three weeks, however, slowly growing, larger, steady bars emerged. These bars had the same wavelength as the ones that formed in another experimental test in which the flow was perturbed by the presence of a transverse plate. The experiment confirms the recent numerical results. Considering that the presence of steady alternate bars is a prerequisite for initiation of meandering, this is now shown to be an inherent feature of alluvial rivers.

Keywords: River morphodynamics, Morphodynamic instability, Migrating and steady bars, Meandering

1 INTRODUCTION

River bars are large sediment deposits that become observable at low flow stages. Alternate bars occur alternately near one side and then near the other side of river channels (Figure 1).

Figure 1. Alternate bars in the River Adige, at Ponte Adige (Italy). Flow from right to left. Google Earth image.

The present wisdom distinguishes migrating from steady bars (Seminara & Tubino, 1989). Their difference lies not only in the migration rates, but also in their sizes, since steady bars are about two times longer than migrating bars. Theoretical studies attribute the origin of migrating bars to spontaneous alluvial channel instability, which is supposed to select the fastest growing ones (e.g. Hansen, 1967; Callander, 1969; Engelund & Skovgaard; 1973, Parker, 1976; Fredsøe, 1978). Instead, the origin of steady bars is attributed to either "resonant" conditions (Blondeaux & Seminara, 1985), since in a resonant system the bar celerity decreases to zero, or the presence of an external flow perturbation, such as a local change in channel geometry (De Vriend & Struiksma, 1984) or a variable discharge (Hall, 2004).

If banks are erodible, migrating bars mainly lead to channel widening; steady bars to local bank erosion and bend growth. For this reason, initiation of meandering was attributed to the formation of steady bars inside straight river channels (Olesen, 1984). This idea met the support of the "bend instability theory" (Ikeda et al., 1981), since the wavelength of incipient meanders was found to be on the order of magnitude of the typical wavelengths of steady alternate bars. The wavelengths of migrating bars, derived as the fastest growing ones, proved too short to give rise to developing meanders. Since river meandering follows from the formation of steady bars, the present wisdom is that also initiation of meandering requires some external forcing or occurs spontaneously only at "resonant" conditions.

Nevertheless, meanders are seen to grow from an initially straight channel with erodible banks also in apparent absence of flow perturbations and at non-resonant conditions (Friedkin, 1945; Rüther and Olsen, 2007). Moreover, a recent numerical investigation shows that steady bars, the precursors of meander point bars, may form spontaneously, albeit slowly, in a straight channel without any flow perturbations and at non-resonant conditions (Crosato & Desta, 2009). With the idea of checking this possibility we performed a laboratory experiment to analyze the temporal evolution of alternate bars in a straight laboratory flume with mobile bed. The experiment was run with a constant discharge for about 10 weeks, to allow for the development of slowly growing steady bars. The experiment was ten times longer that any other experiment of the same type (e.g. Fujita & Muramoto, 1985; Struiksma & Crosato, 1989, Lanzoni, 2000a and 2000b).

1.1 *Experimental set-up*

The experiment was carried out in the Fluid Mechanic Laboratory of Delft University of Technology. The total length of the flume was 26 m; the channel width 60 cm. The bed was covered by a layer of sand having a thickness of 25 cm. The mean diameter of the sediment particles was 0.238 mm. Water and sediment were re-circulated, although water was added in regularly to compensate small losses due to evaporation. The discharge was kept constant at a value of 6.9 l/s.

A wire mesh was introduced at the upstream boundary to dissipate energy, to distribute the flow uniformly and to reduce turbulence. A streamline straightener was placed immediately downstream of the wire mesh, followed by a floating sponge to further reduce turbulence.

Due to the presence of relatively large dunes and ripples, the rough data had to be filtered to clean out the bar signal. The filter used was based on the Matlab software ProcessV3 and optimized for bedforms having wavelength larger than 1 m (bars). Migrating bars characteristics were determined by plotting subsequent filtered bed level profiles, which allowed detecting their size and celerity. Steady bars were identified by averaging the filtered bed level profiles over time, which smoothed out most unsteady signals. Unfortunately filtering followed by time-averaging strongly reduced the bar signal.

Upstream turbulence and perturbation smoothing as well as the measuring and post-processing techniques adopted reduced also the effective length of the channel to about 20 m.

Two experimental tests were carried out. In the first one a transverse plate was placed at the upstream boundary to create a permanent external flow perturbation. This test was meant to study the formation of steady bars as in previous successful experiments (Struiksma & Crosato, 1989; Lanzoni 2000a and 2000b). These bars are generally known as "forced" bars, since they represent the free river response to finite external forcing. In the second test, the transverse plate was removed and the initial bed carefully smoothed out to eliminate all perturbations to the flow. The second test was meant to study the evolution of the bed topography in the same system, but without any external forcing. In this case, according to previous experimental tests (e.g. Fujita & Muramoto, 1985) we could expect the formation of migrating bars only.

2 EXPERIMENTAL RESULTS

2.1 *Test with external forcing*

The experiment started on June 11th 2009 with the lay-out shown in Figure 2. At morphodynamic equilibrium, which was reached within two days, the longitudinal bed slope was 3.54 ‰, the mean water depth 51 mm and the mean velocity 22.5 cm/s.

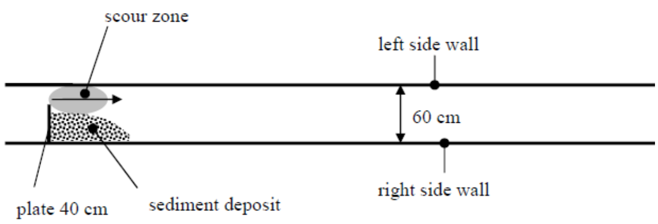

Figure 2. Flume with a transverse plate partially obstructing the inflow.

During the experiment, the longitudinal profiles of the bed and water levels were measured three times per day. The transverse velocity profile was measured across several sections, but with a lower frequency.

Steady alternate bars started to develop immediately after experiment start, forced by the presence of the plate. Their wavelength slowly increased from the initial value of 6.5 m to the final value of about 7.5 m. The latter was reached after about two weeks. Figure 3 shows the temporal evolution of the relative longitudinal bed level profile measured 5 cm from the left side wall. Each curve plotted in the figure represents the bed level profile averaged over one week. Time averaging smoothed out most of migrating bars. Two and a half steady bars became visible.

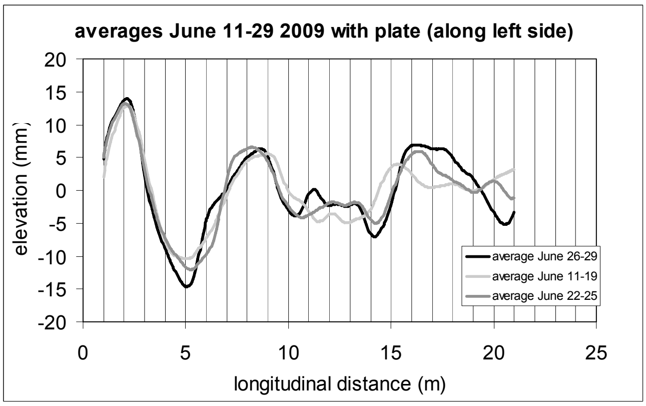

Figure 3. Weekly-averaged bed level profiles measured 5 cm from the left side wall (values relative to the cross-sectionally averaged value of the bed level). Light gray line: average June 11-19. Dark gray line: average June 22-25. Black line: average June 26-29. Test with transverse plate.

Relatively short migrating bars were present from the first day on, but only in the second half of the flume (Figure 4). The area in which migrating bars developed gradually reduced in size, moving downstream. This was due to the gradual dominance of steady bars, starting from upstream.

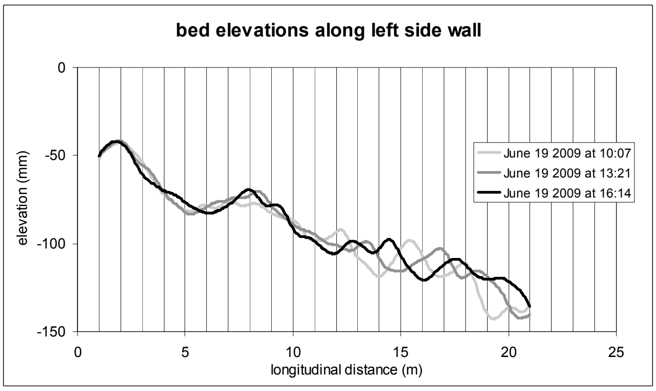

Figure 4. Successive measurements of bed level profile 5 cm from the left side wall (filtered data). Light gray line: June 19 at 10:07. Dark gray line: June 19 at 13:21. Black line: June 19 at 16:14. Test with transverse plate.

The typical wavelength of migrating bars ranged between 2.6 and 4.1 m; their celerity between 22 and 39 cm/hour; their (filtered) amplitude between 5 and 17 mm.

2.2 *Test without external forcing*

The experiment started on June 30th 2009. At morphodynamic equilibrium, which was reached within two days, the longitudinal bed slope was 3.74 ‰; the mean water depth 49 mm; and the mean flow velocity 23.5 cm/s.

The experimental setting does not correspond to the resonant conditions defined by Blondeaux & Seminara (1985), for which the bars migration rates would tend to zero. The small differences in the values of longitudinal slope, water depth and velocity with respect to the previous experiment can be attributed to the absence of the plate, which caused extra resistance in the preceding test.

The transverse profile of depth-averaged flow velocity was measured at three locations, 2.2 m, 12.2 and 22.2 m from the upstream boundary, twice per day for the first 10 days and once every three days during the month July. The time-averaged values of flow velocity near the upstream boundary did not show deviations from uniformity. This allowed excluding the presence of external forcing caused by inflow non-uniformities.

During the first week, the longitudinal profiles of bed and water levels were measured three times per day. The measurements were later carried out twice/day in July, but only once every three days in August. At the end of August the measurements were carried out again with the initial frequency.

On September 5th, 68 days after start, an accident occurred to the pump which jeopardized the progressive bed evolution. The last useful measurement was taken on September 4th.

A single (weak) steady alternate bar started to appear in the upstream half of the flume one day after experiment start already. However, during the first weeks this bar had small amplitude and was unstable, since it disappeared and re-appeared at the same place several times. The initial wavelength of this steady bar was about 7.0 m. Just like in the previous experiment, the wavelength gradually increased. The final value of approximately 7.5 m was reached about three weeks after experiment start. Since then, the steady bar slightly grew in amplitude and two more bars started to appear. These became visible, although not well developed, about six weeks after experiment start. Figure 5 shows the longitudinal profile of the time-averaged bed elevation along the left side wall. The gray line represents the average of the first month and the black line the average of the second month of the experiment.

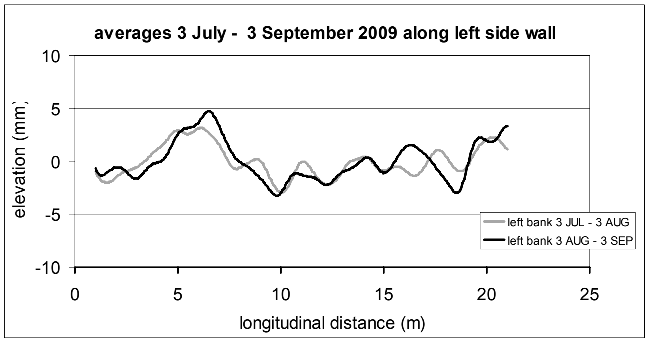

Figure 5. Monthly-averaged longitudinal profiles of bed elevation 5 cm from the left side wall (values relative to the cross-sectionally averaged value of the bed level). Gray line: average 3 July - 3 August. Black line: average 3 August - 3 September. Test without transverse plate.

Unfortunately the experiment had to be stopped when the steady bars were still in development, which means that we cannot show the completion of the bar growth process. Nevertheless, Figure 5 clearly shows the steady waving bed topography.

The time-averaged values of the bed level profiles measured along both the left and the right side walls are plotted in Figure 6. Shallow areas near one side wall correspond to pools near the opposite side wall. This proves that the bed oscillation is due to the presence of steady alternate bars.

The steady bars have a different phase lag than in the preceding test with external forcing, and smaller amplitude, but have the same wavelength. This allows concluding that the steady bars that developed during the test without forcing are of the same type as the traditional "forced" bars. The experiment therefore confirms the numerical results by Crosato & Desta (2009).

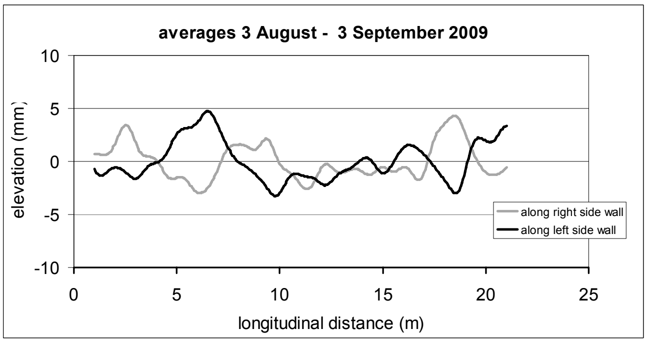

Figure 6. Monthly-averaged longitudinal profiles of bed elevation 5 cm from the left and right side walls (values relative to the cross-sectionally averaged value of the bed level). Gray line: along right side wall. Black line: along left side wall. Test without transverse plate.

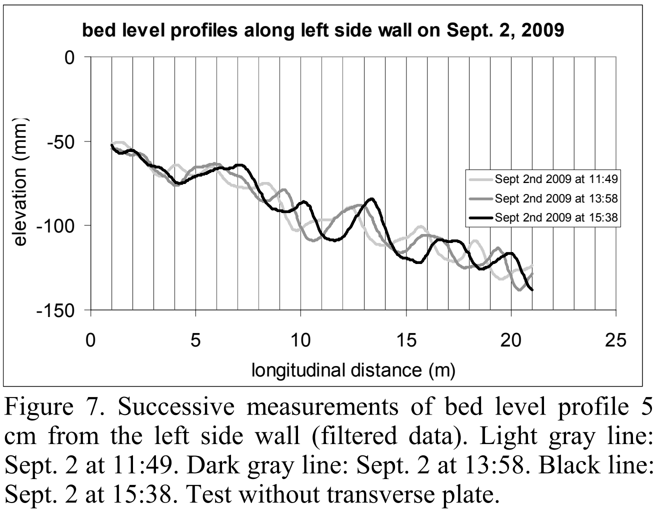

Figure 7. Successive measurements of bed level profile 5 cm from the left side wall (filtered data). Light gray line: Sept. 2 at 11:49. Dark gray line: Sept. 2 at 13:58. Black line: Sept. 2 at 15:38. Test without transverse plate.

Migrating bars started to form from the first day on. Their wavelength ranged between 2.5 and 4.9 m; their celerity between 23 and 40 cm/hour; their (filtered) amplitude between 5 and 16 mm.

Migrating bars were initially present along most of the flume length, but since the steady bar started to appear, migrating bars formed only in the second half of the flume (Figure 7). The situation became similar to the one in the preceding test with the transverse plate, as also observed in previous experiments with forced steady bars (Struiksma & Crosato, 1989 and Lanzoni, 2000a and 2000b). This means that, even in the absence of any upstream disturbance, the channel bed topography gradually acquired the characteristics of a "forced" system.

The sediment transport rate was derived from measurements of sediment concentrations in the water flowing outside the flume at the downstream boundary and roughly estimated in 1.5 g/s. This value is 16 times smaller than the sediment transport rate that was derived with the formula by Engelund & Hansen (1967). The sediment transport rate was derived also on the basis of migrating alternate bars characteristics (amplitude and celerity), using the formula by Simons et al. (1965):

$$q_S = (1-p)c\beta h_b + C \qquad (1)$$

where q_S = sediment transport rate in m^3/s/m, p = porosity (-), h_b= bedform height (m), c = celerity of propagation of the bedform (m/s), β = coefficient to average the cross-sectional area of the bedform (dunes $0.55 \leq \beta \leq 0.6$), C = constant of integration to account for the material not associated with the migration of bedforms (with dominant bed load C = 0).

Assuming porosity p = 0.4, C = 0 (the sediment prevalently moved near the bed), and a sediment density of 2650 kg/m^3, the averaged sediment transport rate resulted in 0.6 g/s. This method underestimates the sediment transport rates. Clearly not all sediment transported by the flow contributed in constructing bars.

3 CONCLUSIONS

The experimental results show that in the test without transverse plate, in which the straight alluvial flume did no have any external forcing nor was the system at resonant conditions, rapidly growing, short, migrating bars developed first. Slowly growing, larger, steady bars developed subsequently, starting from upstream. Their final wavelength was approximately the same as the wavelength of the forced bars that governed the bed topography in the preceding test with a transverse plate. It can be therefore concluded that the steady bars that developed spontaneously in the absence of any external perturbations and at non-resonant conditions were of the same type as those generally known as "forced bars".

In the test with a transverse plate, steady bars dominated the bed topography from the first day on, whereas steady bars formed only after about 3 weeks in the experiment without external forcing. This explains why steady bars were traditionally believed to require geometrical discontinuities. They could be observed in tests with a persistent perturbation only, because the durations of previous experiments were too short. Moreover, filtering of bedforms followed by time-averaging diminishes the signal of steady bars, with the risk that they are not easily recognizable. This might be an additional reason why steady bars have been overlooked in previous experiments.

Our experiment demonstrated that steady bars may form spontaneously, simply as a result of morphodynamic instability, like migrating bars. The major difference between steady and migrating bars is that the former have much smaller growth rates and for this they appear at a later stage.

For the fist time steady bars were observed to develop in an experimental channel as an intrinsic phenomenon. Since steady bars are seen as a prerequisite for meandering, we conclude that meandering also arises as an intrinsic instability of straight alluvial channels also if banks are not easily erodible and channel widening cannot follow migrating bar formation. Resonant width-to-depth ratios, external perturbations and discharge variations are not necessary conditions for the onset of river meandering.

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