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The effect of migrating dune forms on the flow field of an alluvial river

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ABSTRACT: The bed of an alluvial river is highly susceptible to changes during the course of its existence. Besides variations of the large scale topography and plan form of the river, smaller scale dune forms can be observed. These recurring dune forms migrate on top of the large scale topography and can yield local yet important variations in the flow field. In order to study the effect of migrating dune forms on the flow characteristics and consequently the erosive capacity of an alluvial river, an experiment with mobile bed has been carried out in a laboratory flume representing a sharp meander bend. In this experiment, changes to an initially flat, slightly sloped river bed under a steady flow and sediment discharge were observed until a recurring pattern of migrating dune forms could be seen on top of the characteristic pool-bar topography of meander bends. Once the dune forms were established, an Acoustic Doppler Velocity Profiler (ADVP) was placed in several positions alongside the river bend and used to measure the flow depth and flow characteristics under the influence of the passing dunes. Several times during the experiment, the topography was mapped using laser altimetry on a grid of large spatial resolution in order to isolate the dune forms from the large scale topography and determine the dune characteristics and the dune celerity. In this paper the large scale topography and dune characteristics will be shown and the effect of the migrating dune forms on the flow field and the erosive capacity will be discussed in detail.

Keywords: Open-channel flow, Channel bend, Mobile bed, Migrating dunes, Bank erosion

1 INTRODUCTION

Most natural, alluvial rivers tend to meander, which implies their topography undergoes some drastic changes during the course of their existence. Under the influence of the flow field, bed material is transported and subsequently deposited elsewhere, while the outer banks of the successive river bends are eroded. Typically, this leads to a more general large scale pool- point bar topography in the river bends, on which smaller scale 'dune forms' are transported.

This morphological behavior has always been a point of attention among researchers, and more recently there has been a surge of interest in the accurate modeling of the erosion of the outer bank. Thorne (1982) has recognized two dominant processes of bank erosion and retreat: basal erosion and geotechnical bank failure. Basal erosion steepens the bank and intermittently causes mass bank failure. Duan et al. (1999) presented a detailed model of bank retreat through basal erosion, driven by the bank shear stress, in which a depth-averaged flow model, extended with semi-empirical information on the vertical flow structure, is used. Darby and Thorne (1996) proposed a model for the prediction of the probability of geotechnical bank failure and for the amount of collapsed bank material. Nagata et al. (2000) proposed a model that accounts for bank retreat through basal erosion followed by intermittent geotechnical bank failure, employing a depth-averaged flow model and describing the intermittent sediment transport near the bank with a non-equilibrium model.

These models are all based on a depth-averaged flow field, an assumption that, in the case of a meander bend, is not valid. Indeed, a redistribution of the streamwise velocities occurs around the bend. Furthermore, a counter-rational cell of secondary current has been shown to exist near the outer bank, which along with the reduced turbulent activity in this region has a stabilizing effect on the outer bank (Blanckaert and Graf (2001), Blanckaert and de Vriend (2004, 2005)).

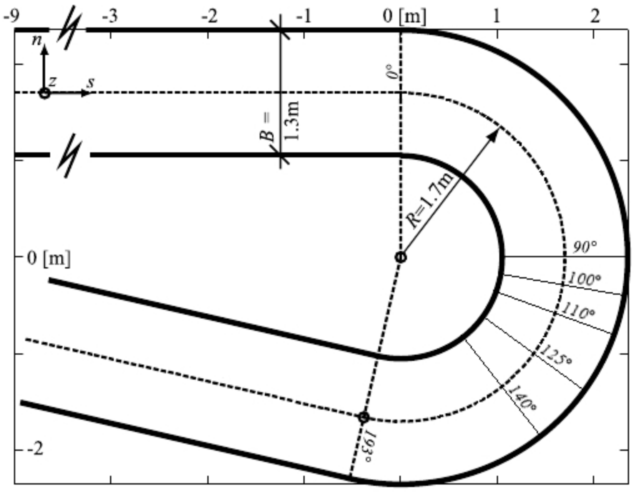

Figure 1. The experimental test setup, with indication of the bend angles at which flow field measurements were carried out.

Thus, the flow field in a meander bend shows a highly complex three-dimensional pattern, of which a more detailed understanding is required. Most existing experimental datasets have been gathered in laboratory flumes with a fixed channel bed. While these experiments are useful to study the flow field in a meander bend, they do not take into account the morphological behavior that is inherent to alluvial rivers (Blanckaert and Graf (2001, 2004), Blanckaert (2009)). Therefore, in order to study the influence of an evolving topography with migrating dune forms on the flow field and consequently on the erosive capacity of alluvial rivers, an open-channel bend experiment with mobile bed is presented in this paper.

2 EXPERIMENT AND MEASUREMENTS

2.1 *Experimental test setup*

The experiment was carried out in the sharply curved laboratory flume shown in Figure 1. A 9 m long straight inflow reach allows the boundary layer to develop fully before the flow enters in the 193° bend of constant radius of curvature, R = 1.7 m, which is followed by a 5 m long straight outflow reach. The flume has a constant width of B = 1.3 m. Quasi-uniform sand with particle diameters in the range d = 1.6 to 2.2 mm is placed on the bed with an initially horizontal cross section, whereas the vertical banks are made of PVC.

At the inlet a reservoir with a feeding mechanism enables the introduction of a constant sediment discharge to the flow, while at the downstream end a settling tank is installed to allow for the deposition of the transported sediment. The settled sediment is then once again used to feed the upstream reservoir, thus forming a closed cycle.

Table 1 summarizes the main hydraulic and geometric parameters of the experiment. The observed flow is rough turbulent ($Re^* = u.k_s/\nu > 70$ where Nikuradse's equivalent sand roughness k_s has been defined according to van Rijn (1984) as three times the sand diameter, Re >> 4000), subcritical (Fr < 1), and very sharply curved ($R/B = 1.31$ and $R/H_m = 17$). The channel aspect ratio of $B/H_m = 13$ is rather high for a laboratory flume, but flow is still less shallow than in most natural rivers.

Table 1: Main hydraulic and geometric parameters of the mobile bed experiment.

Q [l/s]	R [m]	B [m]	H_m [m]	U [m/s]	Fr [-]
0,062	1,700	1,300	0,100	0,477	0,482

Re [-]	R_h [m]	R/B [-]	R/H [-]	B/H [-]
47692,308	0,087	1,308	17,000	13,000

2.2 *Mobile bed experiment*

A mobile bed experiment as the one reported in this paper can be divided into two phases. In the first phase - the transitional phase- the experiment is started over a horizontal bed and a constant sediment discharge is supplied at the flume entrance. Under the influence of the changing flow field, the bed topography in the bend will evolve into a pattern of stable macro features - the characteristic pool- bar topography typically seen in open channel bends - upon which migrating bedforms of smaller scale, such as dunes, are superimposed. During this phase these migrating dunes are closely monitored, with special attention to such characteristics as their height, length, the amount of visible dunes, their inclination and position along the channel bend, and their return period (which ultimately leads to the dune celerity).

Once dunes with similar characteristics start appearing at a steady return period and the amount of ingoing and outgoing sediment are in balance, the experiment is said to be in a state of dynamic equilibrium. From this moment onwards - i.e.the mobile bed phase- the flow characteristics and other parameters of interest are ready to be measured.

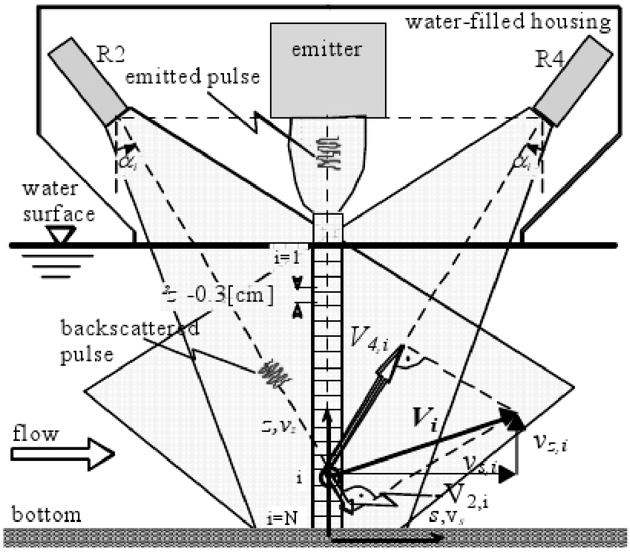

Figure 2. The Acoustic Doppler Velocity Profiler (ADVP).

2.3 *Measurements*

During the experiment, the flow characteristics were measured by means of an Acoustic Doppler Velocity Profiler (ADVP) (Figure 2), and this at several positions along the channel length and width (Table 2).

Table 2: Position of flow field measurements (indicated with OK) along the channel bend.

Distance from outer bank [cm]	Cross section [°]				
	90	100	110	125	140
10	OK	OK	OK	OK	OK
15	OK	OK	OK	OK	OK
20	OK	OK	OK	OK	OK
25	OK	OK	OK	OK	OK
30	OK	OK	OK	OK	OK
35	OK	OK	OK	OK	OK
40	X	OK	X	OK	OK
45	X	OK	X	OK	X
50	X	OK	X	OK	X
55	X	X	X	OK	X

The ADVP, developed at the EPFL, measures the quasi-instantaneous velocity vector with a resolution of turbulence scales. It consists of a central emitter, symmetrically surrounded by four wide-angle receivers, R1 to R4 (only two are visible in Figure 2). From these data, the mean velocity vector, v_m (v_s,v_n,v_z), can be derived, as well as the fluctuating velocity vector, v'_m (v'_s,v'_n,v'_z), the turbulent stress tensor, $v'_j v'_k$ (*j,k=s,n,z*), and even higher-order turbulent correlations, $v'_{ja}v'_{kb}$ (*j,k=s,n,z* and *a,b* integer).

A detailed description of the working principle of the ADVP, its experimental accuracy and its comparison with other velocity meters can be found in Lemmin and Rolland (1997), Hurther and Lemmin (1998), and Blanckaert and Graf (2001).

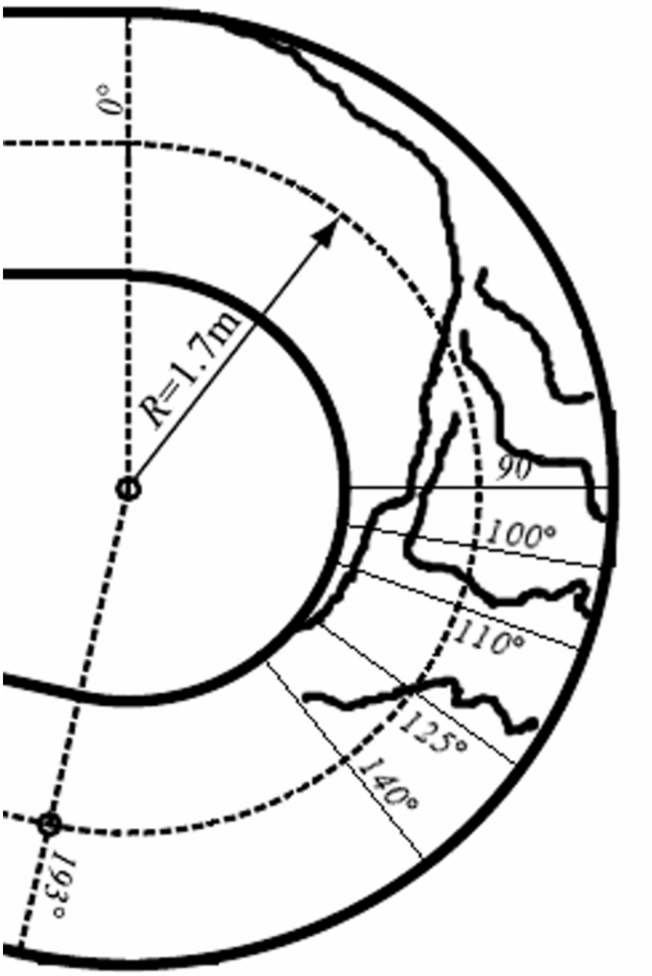

Figure 3. The bed topography during the mobile bed phase.

Besides measuring the flow field with the ADVP, the experiment was also halted several times to map the bed topography by means of laser altimetry on a grid of large spatial resolution (every 5° along the channel bend, with one measuring point every two centimeter along the channel width). By carrying out this topography mapping at different positions of the dunes, the latter could be isolated from the large scale topography and their characteristics and celerity could be determined.

3 TOPOGRAPHY

Figure 3 contains a general image of the bed topography at a certain time during the mobile bed phase, simplified for clarity of discussion. It clearly shows the presence of a point bar that, 70 ° in the channel bend, still covers half the channel width, but quickly draws back to completely disappear at 125°. The water level above the point bar is so shallow that at some places the water even disappears to leave a dry area. Consequently, the whole point bar acts as a dead zone for flow and sediment transport. In between the point bar and the outer bank however, the bottom level shoots down into pools, upon which the dune forms are superimposed.

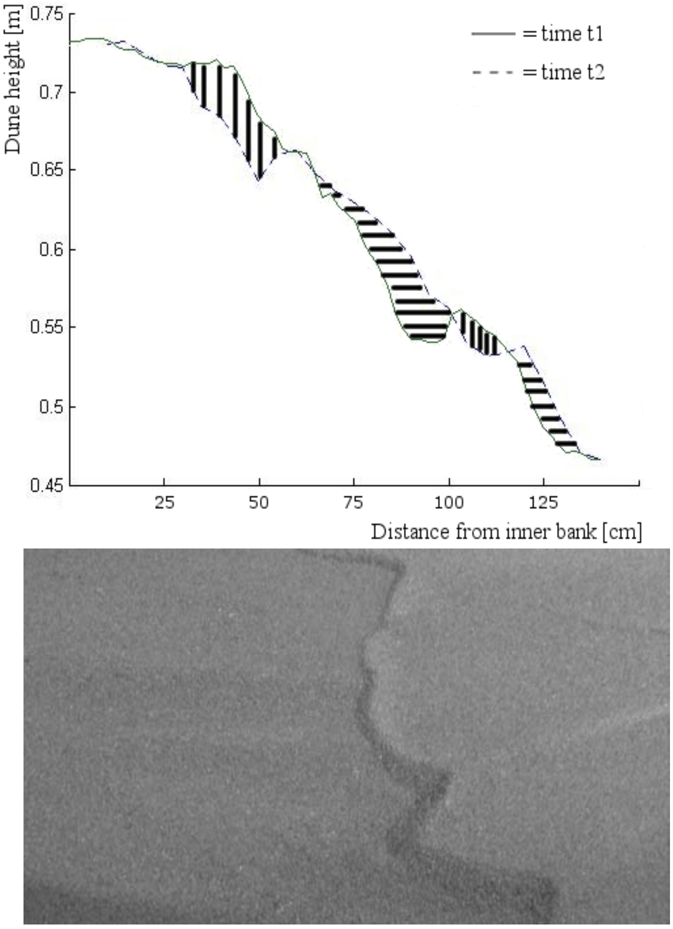

Figure 4. Upper frame: cross section at 90° at two different times t1 and t2. The abscis shows the distance from the inner bank, the ordinate the height above a certain reference level. Horizontally dashed lines indicate higher bottom level at time t2, vertically dashed lines indicate lower bottom level at time t2. Lower frame: detail of a migrating dune.

At any certain moment four dunes could be seen migrating simultaneously through the channel bend. When considering these four dunes as the consecutive positions one dune takes while migrating through the channel bend, the figure shows that the inner bank side of the dune travels at a larger speed than the outer bank side of the dune, an observation that is in agreement with dune forms appearing in actual river bends. However, the distance in between both the outer bank sides and the inner bank sides of the observed dunes stays quasi constant (ca. 15° along the channel bend), which is a sign of dynamic equilibrium. When measuring the time it takes for one dune to migrate to the next position (or for a new dune to appear at the same position = the return period= ca. 12min.), it becomes possible to estimate the average speed with which the dunes migrate through the channel bend. This speed, or dune celerity, was found to be approximately 7.10^{-4} m/s.

The upper frame of figure 4 displays two cross sections that were measured at a bend angle of 90° at two different times during the experiment. Again, the pool-point bar structure is clearly visible. This figure, along with several observations during the course of the experiment (see Figure 4, lower frame) and detailed topographic measurements of the dunes themselves, indicates that the dune height ranges from ca. 2-5 cm.

Since the dune characteristics mentioned above can be found for dune forms in natural rivers, they suggest that the proposed experiment is a valid simulation and the results and conclusions are relevant.

4 FLOW FIELD

As was mentioned above, the flow field characteristics were measured at several places along the channel bend. In order to enable the study of the effects of the migrating dunes on the flow field, at least one dune – and preferably more – had to be captured in one measurement. This led to measuring times ranging from 12 to 30 minutes.

The first results from the flow field analysis will be discussed using measurements carried out at 110° in the channel bend and 20 cm from the outer bank (Figure 5). This measurement exactly captures two passing dunes, starting almost at the top of a first dune and ending at the same point of a third dune. The bottom, white part of the figure can be seen as the changing bed level, while the zone with the actual results symbolizes the water height above the bed level.

In the following, the evolution of the streamwise velocity and turbulent kinetic energy distribution will be discussed.

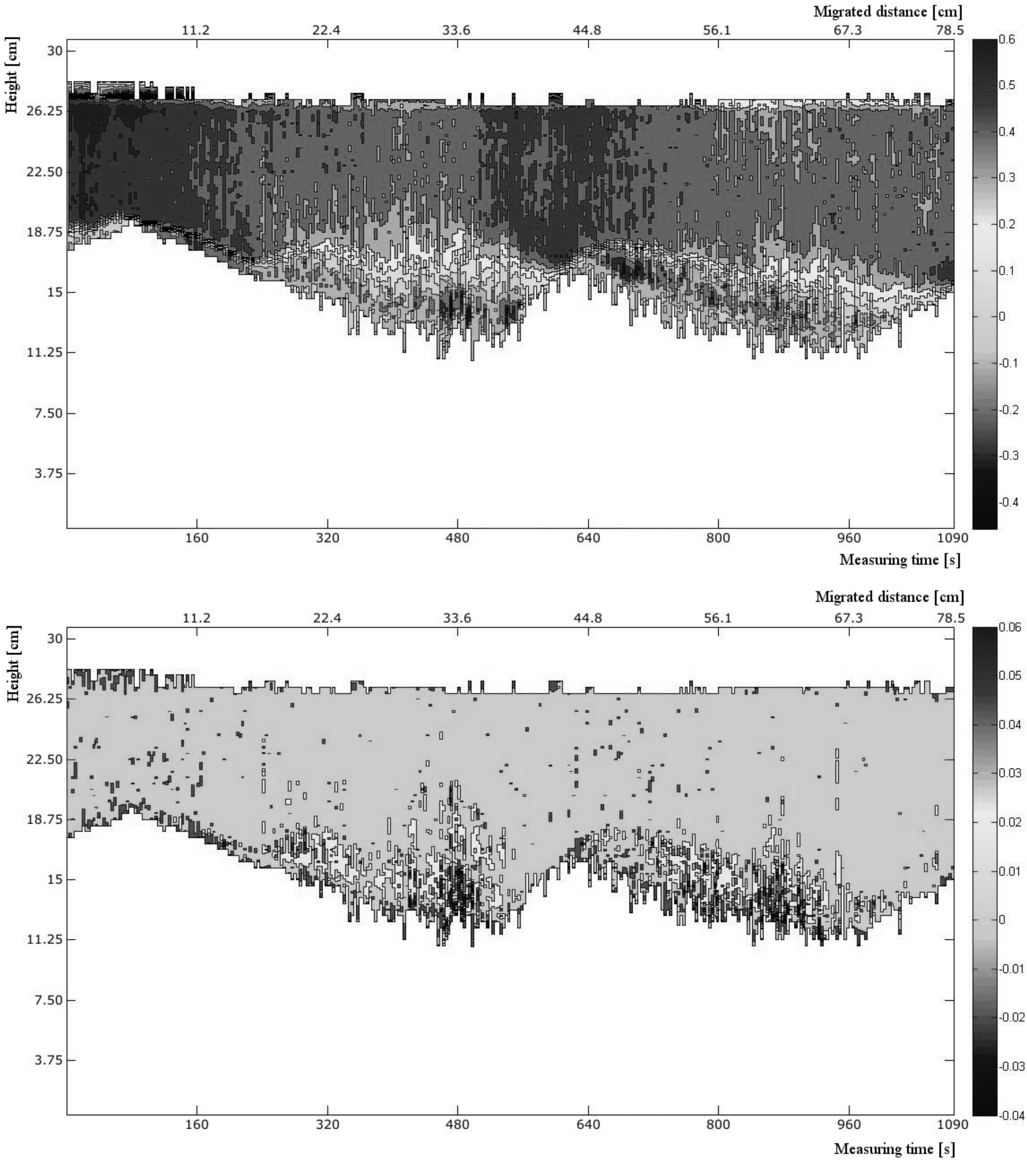

Figure 5. Time evolution of the streamwise velocity (upper frame) and turbulent kinetic energy (lower frame) under influence of a passing dune. The lower abscis shows the time passed since the start of the measurement, the upper abscis shows the distance from the 90° section the dune has travelled since the start of the measurement, and the ordinate shows the distance of the measuring point above a certain reference level. The white zone can be considered to be the bed level, the top measuring point is the water level.

4.2 *Streamwise velocity distribution*

In the upper frame of Figure 5, the time evolution of the streamwise velocity distribution is displayed.

The figure shows that the streamwise velocity has a predictable behavior in the upper part of the water column, as it takes approximately the same value over this entire region, with only a minor drop near the water surface. However, near the bottom surface, the streamwise velocity takes on negative values, indicating backflow. Further analysis of the figure suggests that the water level under which this backflow exists, seems to coincide with the top level of the dune that just passed by, this level being ca. 19 cm in the case of Figure 5.

The existence of this rotational current is easily explained. After the first dune passes the measuring point, the bottom level drops and the extra depth is filled with water flowing at a certain velocity. Further downstream, this water crashes into the dune ahead, and since the water cannot go through this dune, it must break into two directions: backwards and sideways (the cross-stream velocity distributions are not shown, but show similar results: the magnitude of the cross-stream velocity rises in a region right behind the dune), thus creating a rotational cell near the channel bed. This also explains why the height of the rotational zone coincides with the dune height, since this is the height along which the water crashes into the dune.

4.3 *Turbulent kinetic energy distribution*

The time evolution of the turbulent kinetic energy distribution is shown in the lower frame of figure 5. The turbulent kinetic energy follows a similar trend as the streamwise velocity: the turbulent kinetic energy does not change over the top part of the water column, until it reaches a water depth that approximates the height of the previous dune. In this region near the channel bed the turbulent kinetic energy suddenly rises to up to six times the value found in the top part of the water column. This phenomenon is of course closely related to what was described in section 4.1. The drastic changes in the flow field in the regions behind the dunes lead to higher fluctuations of the flow field, which then lead to a higher turbulent kinetic energy.

4.4 *Hypothesis*

These first results seem to indicate that the flow field is scattered and the turbulent kinetic energy rises in the wake of a migrating dune. Since the latter points to an increase of erosive capacity, this leads to believe that the migrating of dune forms along the bed of an alluvial river leads to a local increase of erosive capacity in the wake of the passing dunes. This in turn might lead to an important contribution to the outer bank erosion. Further analysis, focusing on wavelet analysis of the turbulence spectrum, has to be carried out in order to provide more insight in this hypothesis.

5 CONCLUSIONS

In this paper, a mobile bed experiment is presented that investigates the effect of migrating dunes on the erosive capacity of alluvial rivers with sharp open-channel bends. The main conclusions are:

- The channel bed consists of a typical pool-bar topography, with smaller scale dune forms migrating on top of it
- The characteristics of the migrating dunes - height, position and celerity - agree with those of dunes observed in actual alluvial rivers
- The streamwise and cross-stream velocity distributions are affected by the presence of the migrating dunes: the flow field scatters against the dune, and a counter-stream rotation of the flow is observed near the channel bed
- The turbulent kinetic energy noticeably rises in the wake of the passing dune, locally increasing the erosive capacity of the stream

The first results presented in this paper indicate that migrating dunes yield an increase of the erosive capacity of alluvial rivers, but further research is needed before any closing statement can be made in that direction. This research includes employing wavelet analysis to analyse the turbulent kinetic energy with much higher detail.

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