FLOW SEPARATION IN SHARP MEANDER BENDS

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It is well known that abrupt changes in flow direction may lead to flow separation from boundaries. While many smaller or confined meandering rivers have bends sharp enough for flow separation, the problem has surprisingly been ignored in the meandering literature. It is nevertheless essential for understanding and predicting meandering dynamics is small streams in renaturalisation projects. We measured flow structure in experimental sharp bends in the Total Environment Simulator at Hull University over fixed and mobile beds. We found some flow structures similar to those in less sharp bends, but significant differences as well such as lack of relation between flow separation and Froude number. The mobile bed responded dramatically to the sharp bend flow with deep outer-bend pools and high bars up to the water surface.

1. INTRODUCTION

Abrupt changes in flow direction may lead to flow separation from boundaries as frequently found over forms such as bedforms and around engineering structures such as bridge piers. Flow separation has also been observed in sharp river bends (e.g. Leeder and Bridges 1975, Ferguson et al. 2003, Kleinhans et al. 2009). The presence of a separation zone combined with vortex bar formation decreases the channel width and conveyance capacity. This alters patterns of bed and bank erosion in meander bends and can often lead to localized and focused bank erosion. This differs significantly from the flow structure and morphodynamics in less sharp meander bends (e.g. Blanckaert and de Vriend 2003).

Many smaller or confined meandering rivers have bends sharp enough for flow separation. Many such small rivers are presently being renaturalised without understanding the differences between these and larger rivers with more gentle bends. Given the morphological and biological effects of flow separation better understanding is vital for informing environmental management strategies and civil engineering controls (bank protection and shipping depth).

Blanckaert and de Vriend (2003) show that the flow redistribution over the channel in sharp bends depends on the ratio of depth (h) and bend radius (h/R), friction and position in the bend (or length of the bend). Leeder and Bridges (1975) found an empirical discriminator for small tidal flat channels between meander bends with and without flow separation based on Froude number and the ratio of bend radius and channel width (h/W). Despite the recent advances listed above, it is unknown in what conditions flow separates and which factors are important in the actual onset of separation (e.g. how sharp bends must be before the flow separates). Although the above research points to a number of interrelated factors, these have not been systematically investigated a series of bends with varying planform and flow characteristics under controlled conditions.

The overall aim of this work is to explore the interrelationships between flow conditions and bend geometry in the causation of flow separation in systematic experiments and modelling. Our detailed objectives are:

1. determine the overall and detailed flow characteristics including the dimensions of the separated flow zone and turbulence characteristics for a range of flow and bend geometries;
2. investigate the interrelationships between separated flow dimensions and bend geometry;
3. explore the interaction of the separated flow with sediment transport pathways; and

4. process and diseminate the detailed laboratory data and use for model testing to: a) improve ur ability to model time-dependent turbulence and b) enable the models to be scaled up to relevant field scales as predictions to be tested by fieldwork.

2. METHODS

We built a curved flume with two bends in the Total Environment Simulator at Hull University (Fig. 1). The channel had a width of 1 m. The bends had radii of 1 and 2 m.. The walls were constructed of plexiglass at high precision and fixed in place by blocks and plywood. The entire basin was flooded during experiments for further support of the flume walls. The discharge and basin water level were controlled and measured. Pressure sensors recorded water level along the flume. The flow structures in both bends were measured with surface PIV, and ADV array, 3DPIV and ADVP. The general flow conditions are given in Table 1.

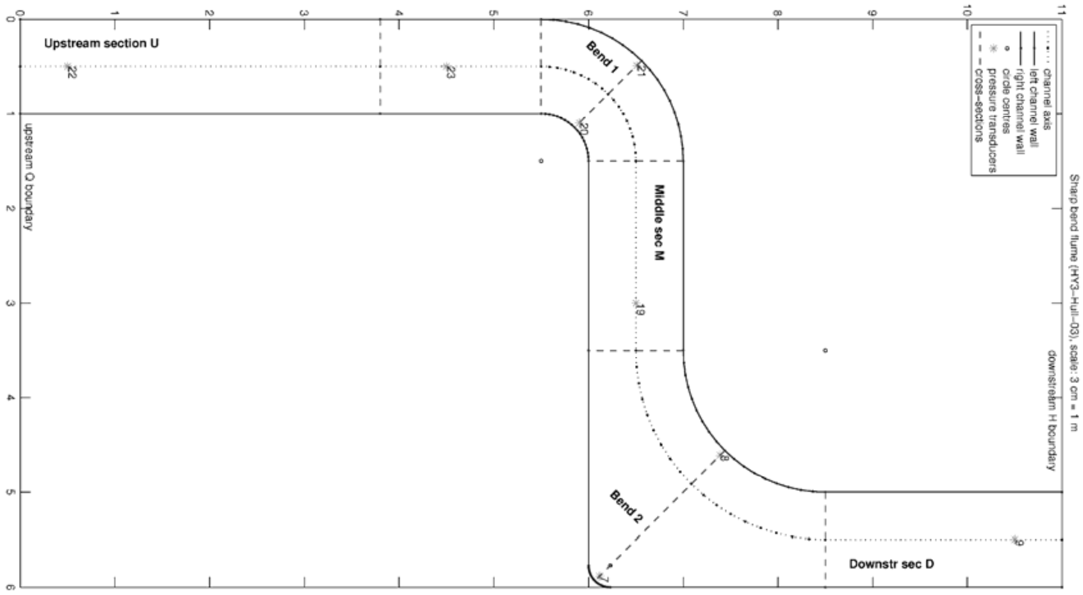

Figure 1. Map of the experimental setup in the tank. Flow is from bottom to top (scale in m). Circular bends are constructed from plexiglass. Not shown: video camera for surface PIV, 3DPIV, ADV array and ADVP.

Table 1. General flow conditions. Width of the flume is 1.00 m. Gradient of gravel bed is $1x10^{-3}$ m/m and of sand bed is about $2\text{-}4x10^{-3}$ m/m.

experiments	depth (m)	Froude number (-)	remarks
small depth high Fr	0.08	0.52	
intermed depth high Fr	0.14	0.43	
large depth high Fr	0.20	0.36	
small depth low Fr	0.08	0.14	nonuniform
large depth low Fr	0.20	0.15	nonuniform
mobile bed	0.15	0.50	50 l/hr sediment feed

Three scaling conditions were posed for the fixed bed. First, the Shields number was below critical for motion. Second, the Froude number was smaller than unity (subcritical flow). Third, the backwater adaptation length was of the order of the flume length so that the gradient is controllable by the downstream water level, and the flow should be uniform. For experiments with much lower Froude number the condition of uniform flow was relaxed. The experiments on fixed bed show that Chezy number is constant rather than Nikuradse roughness length despite the immobile bed.

Three main scaling conditions were posed for the mobile bed. First, the Shields number was above critical for motion and below initiation of significant suspension. Second, the flow was subcritical. Third, the bar regime was underdamped (not unstable) so that bars were forced by the bends. Additional conditions were a high grain Reynolds number so that no ripples form, the Weber number was far above the limit where surface tension effects cease to be important.

The gravel of the immobile bed was unimodal with D_{10} = 9.7 mm, D_{50} = 11.8 mm and D90 = 14.5 mm. At the upstream end coarser gravel was used to prevent erosion and shorten the length of boundary layer adaptation. The sediment of the mobile bed was unimodal coarse sand with D_{10} = 0.61 mm, D_{50} = 0.76 mm and D90 = 0.94 mm. Sediment was trapped and recirculated in units of about 9 l per 10 minutes.

3. EXPERIMENTAL RESULTS

We found three different ways in which flow separates from the main flow in sharp bends (as observed at the water surface): firstly, there is a dead zone starting at approximately 55-60^{o} through the bend, which is the phenomenon we were looking for (Fig. 2,3); secondly, there is a small zone of weak recirculation immediately downstream of the bend, driven by the reverse pressure gradient caused by the sudden change in curvature; thirdly, there is a large recirculation zone in the expanding outer bend.

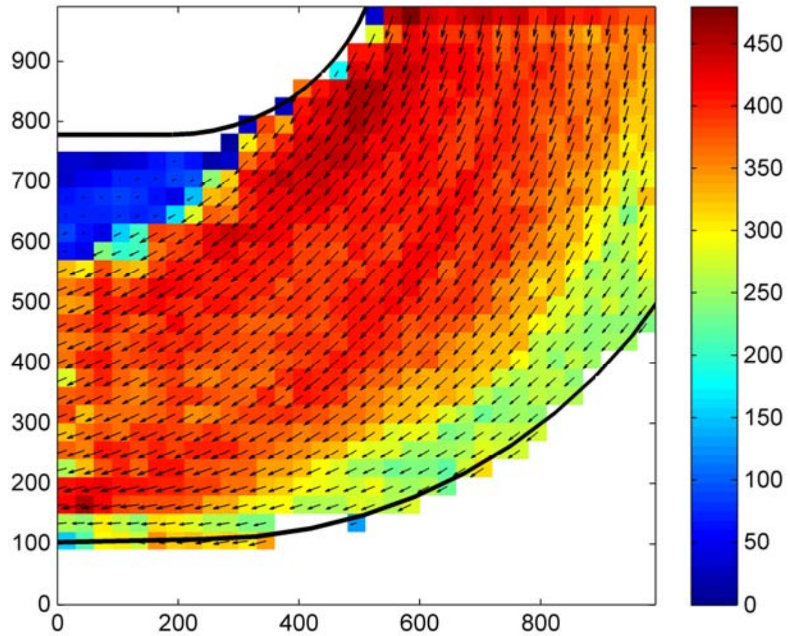

Figure 2. Surface PIV data of 0.14 m depth condition in the first bend. Flow from top right to bottom left. Black lines indicate banks. Note the upwelling on the outer bank and the dead zone in the downstream inner bend. Coordinates in mm; velocity in arbitrary units.

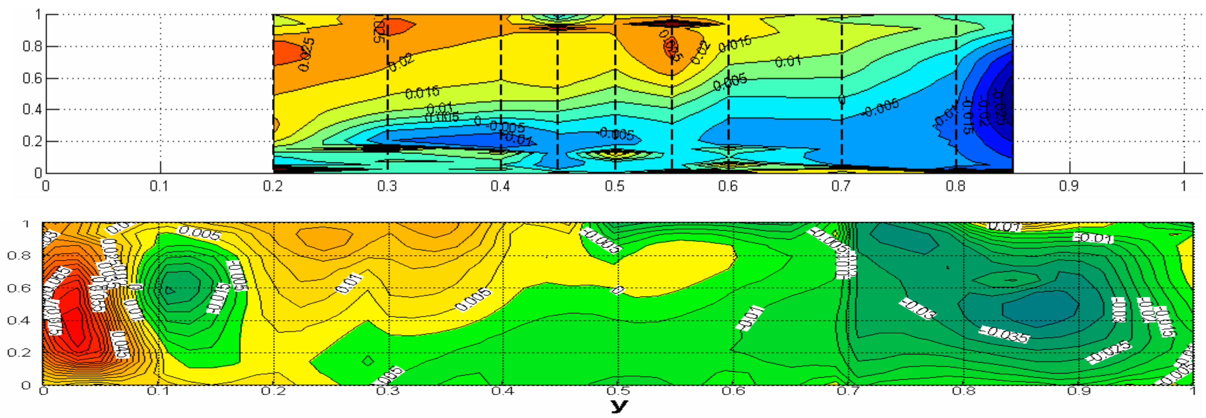

Figure 3. Pattern of the vertical velocity for the 0.14 m depth condition in the downstream half of the upstream bend. Distance from the inner bank on the horizontal axis and normalized flow depth on the vertical axis. Undistorted scale. (top) ADVP measurements in vertical profiles indicated by dashed lines; (bottom) 3D PIV measurements.

We observed that the flow separation patterns do not change very much in different water depths and Froude numbers. This is a surprising finding given theoretical relations between spiral flow, water depth and Froude number and empirical results of Leeder and Bridges (1975). Apart from that, the three-dimensional flow structures, as far as understood from preliminary processing and observations, resembles that in less sharp bends: there is a dead zone in the inner bend downstream of the apex, there is a helical flow in the middle of the channel, and there is a considerable outer-bank cell. In the second bend some of the circulation is inherited from the first bend.

The morphological response of a mobile sand bed was quite dramatical (Fig. 4): deep scours developed where the flow impinged on the outer banks, and bars built up nearly to the water surface in the dead flow zones. The sediment in the expanding outer bend was removed entirely.

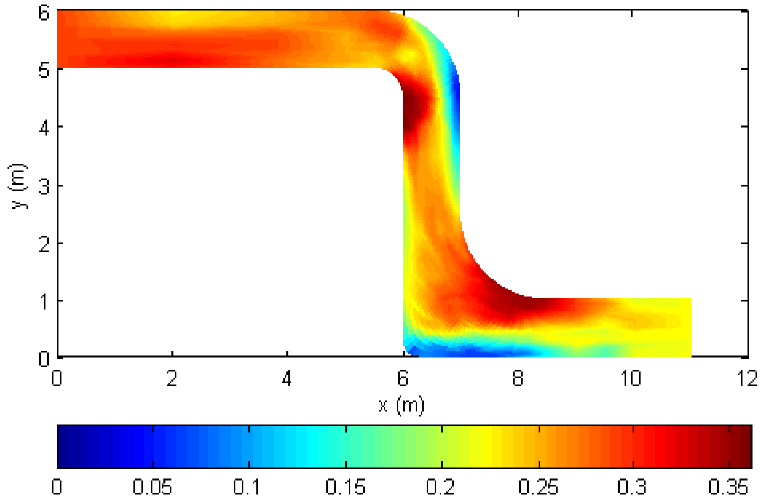

Figure 4. Bed level above TES floor of the mobile bed after about 36 hours of flow. Morphology is about in equilibrium except for a trend of gradient increase due to slight overfeeding. Scale in m.

4. PRELIMINARY CONCLUSIONS

Based on the experiments we arrive at the following preliminary conclusions:

- For smoothly curved channels there is no hard flow separation zone with recirculating flow such as observed in field cases (Leeder and Bridges 1975, Kleinhans et al. 2008). This indicates that such separation is caused by nonuniform width and bank irregularity.
- A dead zone exists near the inner bank in the downstream half of sharp bends. In comparison to experiments by Blanckaert and de Vriend (2003) this zone was better developed and present in all experimental settings.
- The strong bend flow and the focus of flow on the downstream outer-bend causes an extremely deep pool and a bar up to the water surface. Recirculating flow behind this bar is reduced over time as sediment is trapped in the dead zone.

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