# Influence of complex bedform morphology on flow and shear stress

A. Lefebvre *MARUM – Center for Marine Environmental Sciences, Germany – alefebvre@marum.de*
A. J. Paarlberg *HKV CONSULTANTS, Lelystad, the Netherlands – a.paarlberg@hkv.nl*
C. Winter *MARUM – Center for Marine Environmental Sciences, Germany – cwintere@marum.de*

ABSTRACT: This study investigates how complex morphology of natural bedforms affects the flow compared to the well-studied triangular bedforms. Four bed profiles from two rivers are analysed to determine a typical bedform morphology. The most commonly occurring morphological elements are a stoss side made one segment and a lee side made of a gently sloping upper lee side and a relatively steep (6-21°) slip face. The Delft3D modelling system is used to simulate flow over fixed bedforms with various morphology inspired by the analysis of the naturally occurring bedforms. For slip face angles smaller than 18°, no reversed flow is observed. For slip face angles steeper than 18°, the size of the flow separation zone increases with increasing slip face angle. Both shear stress and turbulence increase with increasing slip face angle and are only marginally affected by the dimensions and positions of the upper and lower lee side.

## 1. INTRODUCTION

The majority of laboratory or numerical modelling studies on the hydrodynamics above bedforms have investigated angle-of-repose bedforms of idealised shape; that is, bedforms with a lee side angle of 30° having a triangular or sine-shaped stoss side and straight lee side shape. However it is now recognised that many large rivers are characterised by bedforms with lee side slopes lower than the angle-of-repose, the so-called low angle bedforms (Best, 2005); field measurements also show that natural bedforms mostly display a morphology that differs from the triangular or sine-straight profiles (e.g. Best and Kostaschuk, 2002, Kostaschuk and Villard, 1996, Parsons et al., 2005) with stoss and lee sides having one or more brink points, i.e. breaks in the bed slope (Figure 1). Over bedforms with a straight angle-of-repose lee side, the flow separates at the crest, a reverse flow forms above the lee side, and a turbulent wake is produced at the flow separation point, extending and expanding downstream (Best, 2005). Energy transformation in the flow separation zone and associated turbulent wake are largely responsible for form roughness, which constitutes an important part of the shear stress in environments where bedforms are present (Kostaschuk and Villard, 1996, Lefebvre et al., 2014a, Smith and McLean, 1977). The angle of the lee side is often thought to be a crucial component of bedform morphology because of its influence on the flow: a permanent flow separation zone is present only over steep lee sides and is temporary or absent over bedforms with a gentle lee side (Best and Kostaschuk, 2002, Kostaschuk and Villard, 1996). Turbulence production, hence form roughness, is therefore reduced over low angle bedforms compared to angle-of-repose bedforms. Commonly, the average slope between the crest and trough (i.e. the average angle of the lee side) has been used to assess whether a flow separation zone is present. However, bedforms with an average lee side angle too gentle for the flow to separate may still have a steep slip face over which flow separation occurs (cf. Figure 1). Therefore, taking into account only the crest and trough positions and assuming a triangular bedform shape may lead to a wrong estimation of whether there is flow separation and the intensity of turbulence and shear stress.

Thus this study aims to compare the influence that bedforms with a typical natural morphology have on the flow compared to triangular bedforms.

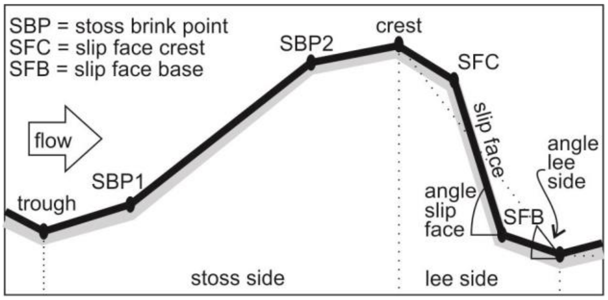

Figure 1. Bedform profile including brink points.

## 2. BEDFORM MORPHOLOGY

### 2.1. Methods

Field data of four 1 km-long longitudinal profiles, extracted from two river bed datasets, were used to characterise bedform morphology. The profiles were extracted from three-dimensional bathymetry of the Rio Paraná, Argentina (Parsons et al., 2005) were each profile contains around 20 bedforms (ca. 1.5 m high and 50 m long, average depth of 7 m) and the Lower Rhine, the Netherlands (Frings, 2007) where each profile contains around 70 to 90 bedforms (height 0.6 m, length 15 m and water depth 9 m).

The positions of crests and troughs of individual bedforms were determined using a bedform-tracking-tool (Van der Mark and Blom, 2007). Thereafter, typical bedform features in the form of brink points (Figure 1) were sought based on bed slopes. In particular, the slip face has been defined as the part of the bedform lee side which has angles steeper than 5°. The horizontal length, height and angle of each segment were calculated.

### 2.2. Results

Most of the stoss sides of the investigated bedforms are made of one segment (58% of all considered bedforms). Another common type features one brink point (26%). The lee side most often is best represented by two segments, the upper stoss side and the slip face (50% of all considered bedforms). One third of the bedforms feature two brink points (33%).

Interestingly, the slip face angles never reach the angle-of-repose, being on average 14° (Table 1), and less than 21° for 95% of the bedforms; the steepest slip face determined from our dataset has an angle of 24.4°.

Table 1: Summary of bedform morphology results.

| Element | Average value |
|---|---|
| Bedform length ($L_b$) | 25.2 m |
| Bedform height ($H_b$) | 0.9 m |
| Stoss side length | 17.5 m (18.5 $H_b$) |
| Upper lee side length | 5.5 m (6 Hb) |
| Upper lee side angle | 1.9° |
| Slip face length | 3.0 m (3.6 Hb) |
| Slip face angle | 13.8° |
| Lower lee side length | 1.6 m (1.9 Hb) |
| Lower lee side angle | 2.5° |

## 3. MODELLING EXPERIMENTS

### 3.1. Methods

The non-hydrostatic Delft3D modelling system has been used to setup a two-dimensional vertical (2DV) numerical model to simulate horizontal and vertical velocities, turbulent kinetic energy (TKE) and water levels above fixed bedforms. The model has been shown to reproduce flow separation, turbulence and shear stress over idealised, angle-of-repose bedforms under unidirectional flow conditions (Lefebvre et al., 2014b) and velocities, TKE and water levels in a tidal environment over natural bedforms (Lefebvre et al., 2014a).

Simulations were performed on a 2DV plane Cartesian model grid over a fixed bed composed of 20 similar bedforms with a logarithmic velocity profile at the upstream boundary, and a water surface elevation of 0 m at the downstream boundary.

Five series of simulations were carried out; for all simulations, the bedform height and length, the length of the stoss side and the water depth were taken from the average dimensions calculated from the analysed bedform (Table 1) and the dimensions of the upper and lower lee side and the slip face were kept within the range determined from the analysis of the natural bedform shape.

The first series of simulations (Figure 2a) examines the influence of slip face angle, which is hypothesised to be the morphological parameter having the strongest effect on how bedforms impact the flow. The second experiment investigates the influence of the dimensions of the upper lee side by varying the position of the slip face crest (Figure 2b). Thirdly, a series of simulations tests the influence of the lower lee side by changing the position of the slip face base (Figure 2c). In a fourth series of simulations, the length and height of the upper and lower lee sides are simultaneously varied to change the position of the slip face (Figure 2d). Another set of simulations is carried out to test the influence of the angle of the upper lee side. (Figure 2e).

From the simulation results, the horizontal and vertical velocities and the TKE above the 16th bedform (of total 20 bedforms) are analysed. The position and size of the flow separation zone, when present, is calculated following the method detailed in Lefebvre et al. (2014b). The average slope of the water level, which has adjusted to the flow conditions over the bedform field, is used to calculate the total shear stress.

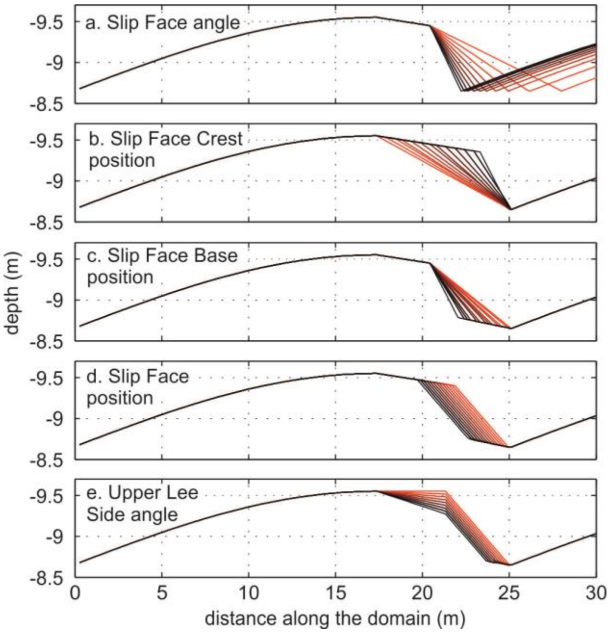

Figure 2. Simulated bedforms.

## 3.2. Results

Simulated horizontal velocities show the general pattern of flow over bedforms with flow acceleration over the bedform stoss side and deceleration over the bedform lee side. For slip face angles smaller than 18° the flow decelerates considerably but no reverse flow develops. For slip face angles steeper than 18°, the flow separation zone is first restricted to the trough and is getting larger as the slip face angle increases. For a slip face angle of 24° (the steepest slip face tested), the flow separation zone starts just under the slip face crest and extends to a distance of 4.8 height of the slip face. This pattern is recognised over all bedforms of all simulations, with the presence of the flow separation zone being related only to the angle of the slip face and not to the presence or the size of the upper or lower lee sides.

When there is no flow separation zone, the TKE along the bedform is low, with a small region of higher turbulence recognisable over the trough. As the flow separation zone appears, TKE increases and a noticeable wake forms. For a full size flow separation zone, TKE is high with a well-defined wake extending from the crest along the flow separation line and above the following stoss side.

Shear stress increases with increasing slip face angle, being lowest for the smallest slip face angle tested and highest for the steepest face angle (Figure 3a).

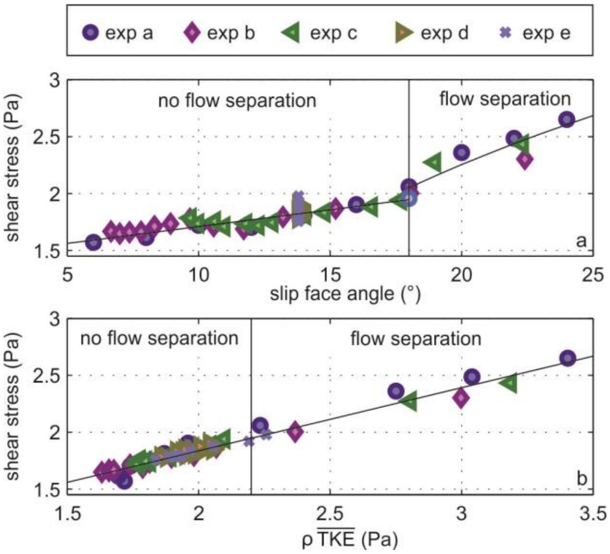

Figure 3. Shear stress as a function of (a) slip face angle and (b) mean TKE along the bedform; refer to Figure 2 for detail of the experiments.

The morphology of the lee side has little influence on the shear stress; shear stress of experiments having varying slip face angles and upper and lower lee side dimensions varies in the same range as shear stress from experiments where only the slip face angle is varied. Shear stress increases linearly with the mean TKE along the bedform (Figure 3b).

## 4. CONCLUSIONS

The analysis of bed profiles from two alluvial environments shows that common morphological elements of bedforms detected along these profiles are a stoss side that is best described by a single segment and a lee side composed of two segments, a gently sloping upper lee side and a relatively steep slip face. The slip face angles never reach the angle-of-repose and are in the range of 6 to 21°.

Numerical simulations with a non-hydrostatic model show how different bedform shapes influence the flow and shear stress over bedforms. The occurrence and length of a flow separation zone is mainly determined by the slip face angle: no flow separation is detected for slip face angles smaller than 18°; for slip face angle steeper than 18°, the size of the flow separation zone and the strength of the turbulent wake are increasing with increasing slip face angle. The shear stress is principally influenced by the slip face angle through turbulence intensity and little affected by the dimensions or positions of the upper and lower lee sides.

This work contributes to the characterisation of typical river bedform morphology. It is important to note that the average slip face angle determined from the bed profiles is 14°, over which no flow separation is predicted, and shear stress and turbulence are much lower than over angle-of-repose bedforms. Thus it is likely to be inaccurate to assume enhanced shear stress simply due to the presence of bedforms. Instead, the slip face angle (and not only the average lee side angle) should be determined in order to correctly parameterise the influence of bedforms on the flow.

## 5. ACKNOWLEDGMENT

This study was funded through the DFG Research Center/Cluster of Excellence “The Ocean in the Earth System”. The authors wish to thank R. M. Frings and D. R. Parsons for providing the multibeam echosounder data used in the analysis.

## 6. REFERENCES

Best, J. 2005. The fluid dynamics of river dunes: A review and some future research directions. Journal of Geophysical Research 110 (F04S02): 21.

Best, J. and Kostaschuk, R. 2002. An experimental study of turbulent flow over a low-angle dune. Journal of Geophysical Research 107 (C9): 3135.

Frings, R.M. 2007. From gravel to sand. Downstream fining of bed sediments in the lower river Rhine. Utrecht University, the Netherlands. Also published as Netherlands Geographical Studies 368, Royal Dutch Geographical Society, Utrecht.

Kostaschuk, R. and Villard, P. 1996. Flow and sediment transport over large subaqueous dunes: Fraser River, Canada. Sedimentology 43 (5): 849-863.

Lefebvre, A., Paarlberg, A.J., Ernstsen, V.B. and Winter, C. 2014a. Flow separation and roughness lengths over large bedforms in a tidal environment: A numerical investigation. Continental Shelf Research 91 (0): 57-69.

Lefebvre, A., Paarlberg, A.J. and Winter, C. 2014b. Flow separation and shear stress over angle of repose bedforms: a numerical investigation. Water Resources Research 50 (2): 986-1005.

Parsons, D.R., Best, J.L., Orfeo, O., Hardy, R.J., Kostaschuk, R. and Lane, S.N. 2005. Morphology and flow fields of three-dimensional dunes, Rio Paraná, Argentina: Results from simultaneous multibeam echo sounding and acoustic Doppler current profiling. Journal of Geophysical Research 110 (F4): F04S03.

Smith, J.D. and McLean, S.R. 1977. Spatially averaged flow over a wavy surface. Journal of Geophysical Research 84 (12): 1735-1746.

Van der Mark, C.F. and Blom, A. 2007. A new and widely applicable tool for determining the geometric properties of bedforms. University of Twente, Enschede, Netherlands.