Three-dimensional flow above a natural bedform field

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ABSTRACT: Large bedforms in rivers and coastal seas usually develop as extensive fields of three-dimensional (3D) dunes. The mutual interaction of flow and 3D bedforms has until now been studied mainly above idealised bedforms. The present work examines 3D flow over a natural bedform field from the Rio Paraná (Argentina) using the Delft3D modelling system. The presence and position of flow reversal and turbulent wake are found to be related to the presence and properties of the slip face (portion of the lee side having a slope > 15°) and not to that of the crest or the bedform height, as is usually assumed. Therefore, in order to correctly describe and model the effect of bedforms on flow, detailed bedform morphology, including slip face presence and 3D properties, needs to be calculated.

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1 INTRODUCTION

Traditionally, the effect that bedforms have on flow has been investigated in laboratory flumes over two-dimensional (2D) bedforms having an angle-of-repose (30°) lee side and a relatively simple shape (e.g. Lefebvre et al., 2014b, Lefebvre and Winter, 2016, Maddux et al., 2003, Omidyeganeh and Piomelli, 2013, Venditti, 2007). Over such bedforms, the flow field shows different regions (Best, 2005); (1) a flow separation zone over the bedform lee side in which flow reversal is observed; (2) a shear layer and turbulent wake region, originating at the crest, extending, and expanding downstream; (3) an internal boundary layer that grows from the reattachment point beneath the wake toward the crest; and (4) an outer, overlying region. The flow separation zone and associated turbulence production in the wake are largely responsible for the so-called form roughness, which constitutes an important part of the shear stress in environments where bedforms are present and thus a major factor in the calculation and prediction of hydrodynamics and sediment transport.

It is now recognised that many large rivers are characterised by low-angle bedforms with lee side slopes lower than the angle of repose (Best, 2005). Over such bedforms flow no permanent flow separation is observed; no distinct wake is found, only a region of slightly elevated turbulence (Lefebvre et al., 2016). The threshold between low and high-angle bedforms is usually given to be between 10 and 20° (Lefebvre and Winter, 2016). Natural bedforms also have a complex shape, frequently showing a lee side made up of a gentle upper lee side, or crestal platform, and a steeper slip face (Lefebvre et al., 2016).

Bedforms in rivers and in coastal tidal environments often develop into large fields. These fields are inherently three-dimensional (3D), with only special conditions leading to two-dimensional bedform fields (Rubin, 2012).

Bedform three-dimensionality has been recognised by the early work of Allen (1968); since then, only some aspects of three-dimensionality, mainly the influence of crest line sinuosity and height variations, have been systematically studied however only over regular geometric pattern and at laboratory scale (Maddux et al., 2003, Omidyeganeh and Piomelli, 2013, Venditti, 2007) with the notable exception of the field study of Parsons et al. (2005). These studies allowed to characterise some aspects of flow over regular 3D bedforms (Maddux et al., 2003, Omidyeganeh and Piomelli, 2013, Venditti,2007). Over profiles having the little height variations, or over nodes, streamwise flow is accelerated, crosswise flow develops, and a strong downward directed flow induces a vertical suppression of turbulence with a reduced flow separation zone and a suppressed wake. Over profiles with strong height variations, or over a lobe, crosswise flow is limited and vertical flow is positive; flow separation and wake are strong and diffused upward. Although variations of flow patterns are seen depending on bedforms three-dimensionality in the field, they are more difficult to precisely interpret due to instrument limitations (Parsons et al., 2005).

The present work aims at investigating the details of 3D flow over a natural bedform field using numerical modelling.

2 NUMERICAL MODEL

2.1 Modelling system

Delft3D is a process-based open-source integrated modelling system developed to simulate flow and transport in river, estuarine and coastal areas (Deltares, 2014). In the Delft3D-FLOW module the 3D non-linear shallow water equations derived from the three-dimensional Navier-Stokes equations for incompressible free surface flow are solved. The non-hydrostatic Delft3D modelling system has already been successfully used in 2DV to simulate horizontal and vertical velocities, turbulent kinetic energy (TKE) and water levels above fixed bedforms (Lefebvre et al., 2014a, Lefebvre et al., 2014b, Lefebvre et al., 2016, Lefebvre and Winter, 2016).

The model is now set up to simulate three-dimensional flows over bedform fields by extending the model domain into the cross-stream direction. All simulations are performed on a 3D Cartesian model grid discretising a fixed bed, i.e. no sediment transport is modelled. The model has been calibrated against laboratory measurements of flow above idealised 3D bedforms from Maddux et al. (2003).

2.2 Model set up

The model is used to simulate flow over a natural bedform field collected in the Rio Paraná, Argentina by Parsons et al. (2005). The investigated river bed is covered with large dunes (1.2 to 2.5 m high and 45 to 85 m long) as well as smaller bedforms mainly situated on the stoss side of the large dunes. The chosen domain excludes local morphological features and is detrended to exclude any large scale slope. Two open boundaries are set, one entrance and one exit, and two closed boundaries, to make the domain model resemble, to some extent, a field-scale flume.

The chosen domain size is 675 m long and 200 m wide, with a grid cell of 0.5 m. Forty non-equidistant vertical layers are set, having a size of 0.15 m from the lowest point of the bed to 0.5 m above the highest crest, before slowly increasing to 0.45 m at the water surface. The entrance boundary is set with velocities of 1 m s^{-1} to resemble flow conditions during data collection, which supposedly created and maintained the measured bedforms.

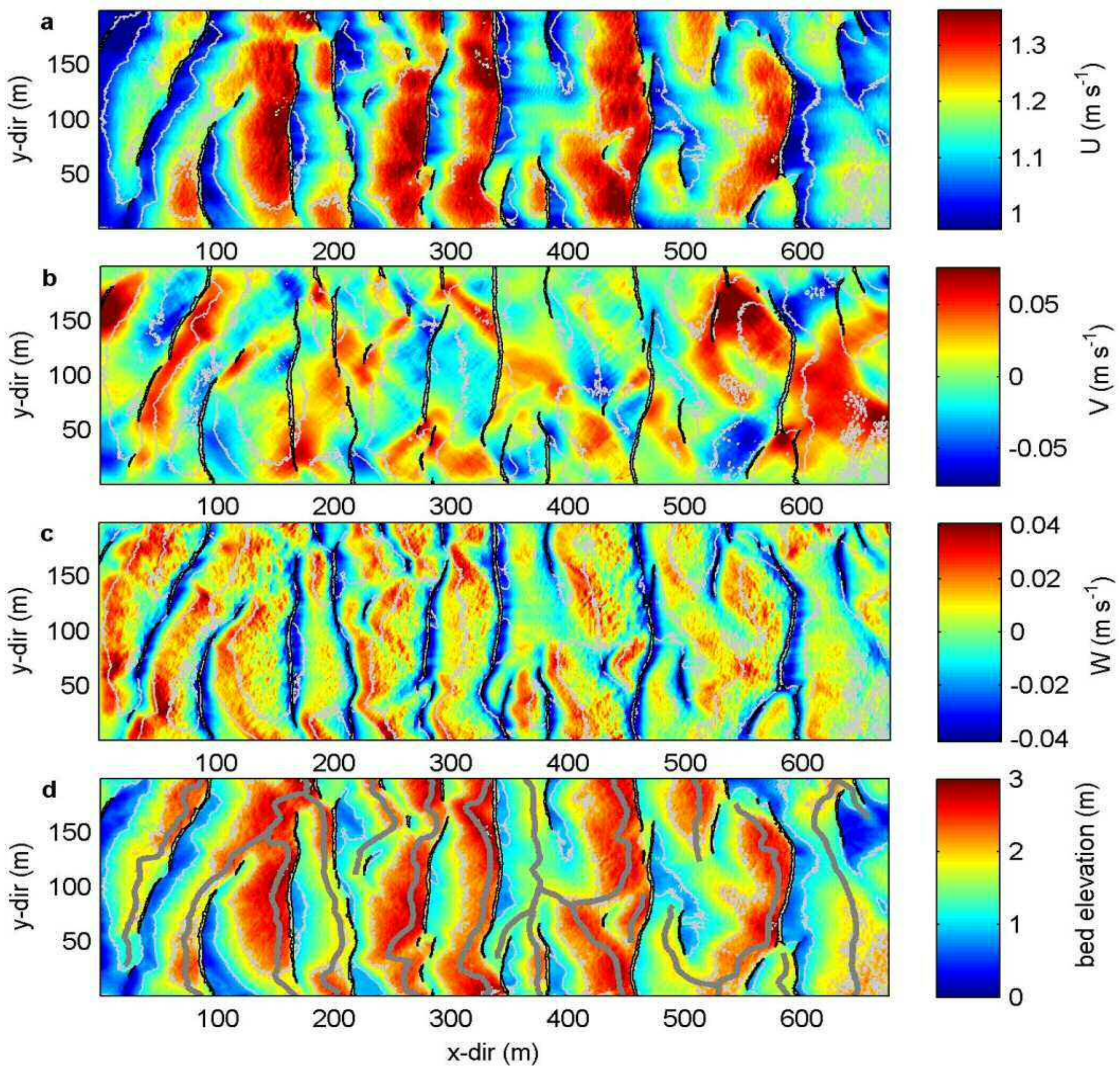

Figure 1. Depth-averaged stream wise velocity U (a), crosswise velocity V (b) and vertical velocity W (c) over the model domain (d); in all figures, the black lines show the position of the slip faces and the thin grey lines highlights the bed elevation contours; in Figure d, the thick grey lines show the crest line positions; flow is from left to right

3 RESULTS

The depth-averaged stream wise velocity (Figure 1a) shows the expected patterns of flow acceleration over the stoss side and flow deceleration over the lee side; more precisely, fast flow before the slip face and slow flow over the slip face. The topographic forcing of the flow is seen as a strong crosswise velocity observed in the regions where the slip faces are curved (Figure 1b). The depth-averaged vertical velocity (Figure 1c) follows the expected patterns above bedforms, with upward velocity above the stoss sides and downward above the lee sides, with the strongest downward velocity being found over the slip faces.

In order to better assess the mutual influence of bed morphology and flow properties, the positions of the flow separation zones and turbulent wakes are calculated. The flow separation zones are defined as portions of the flow where negative stream wise velocity are found. The height of the flow separation zone is calculated for each point where a negative velocity is found as the height where the upstream directed flow is compensated by the downstream directed flow. Along each transect, the length of the flow separation zone, L_{FSZ}, is calculated as the horizontal distance between the first and the last negative point between each crest and trough. The wake is detected as positions where TKE is higher than the TKE 98th percentile. Along each transect and between each successive crest, the length of the wake is calculated as the horizontal distance between the beginning of the slip face and the maximum extent of the wake.

Figure 2a shows the position of the detected flow separation zones and wakes in relation the bedform crestlines and slip faces. Flow separation zones and turbulent wakes are found behind slip faces and are absent above bedforms with a gentle lee side. The length of the flow separation zone is only poorly related to the bedform height but it is strongly related to the height of the slip face (H_{sp}) L_{FSZ} = 4.99 H_{sp} (R^2 = 0.74, Figure 2b).

Although a flow separation zone is found behind most slip faces, 18% of the slip faces are not followed by flow reversal. These are mainly slip faces with a strong angle compared the flow (i.e. not transverse to the flow), or relatively gentle and small slip faces. The presence of a flow separation zone is therefore predicted to happen behind slip faces with an absolute direction less than 25°, a height greater than 0.3 m and maximum angle steeper than 18°.

The length of the wake shows a weak relation to bedform height but a strong relation the slip face height L_w = 13.3 H_{sp} (R^2 = 0.68, Figure 2c). Similarly to the flow separation zone, the wake is more likely to appear behind high and steep slip faces than behind gentle and low ones.

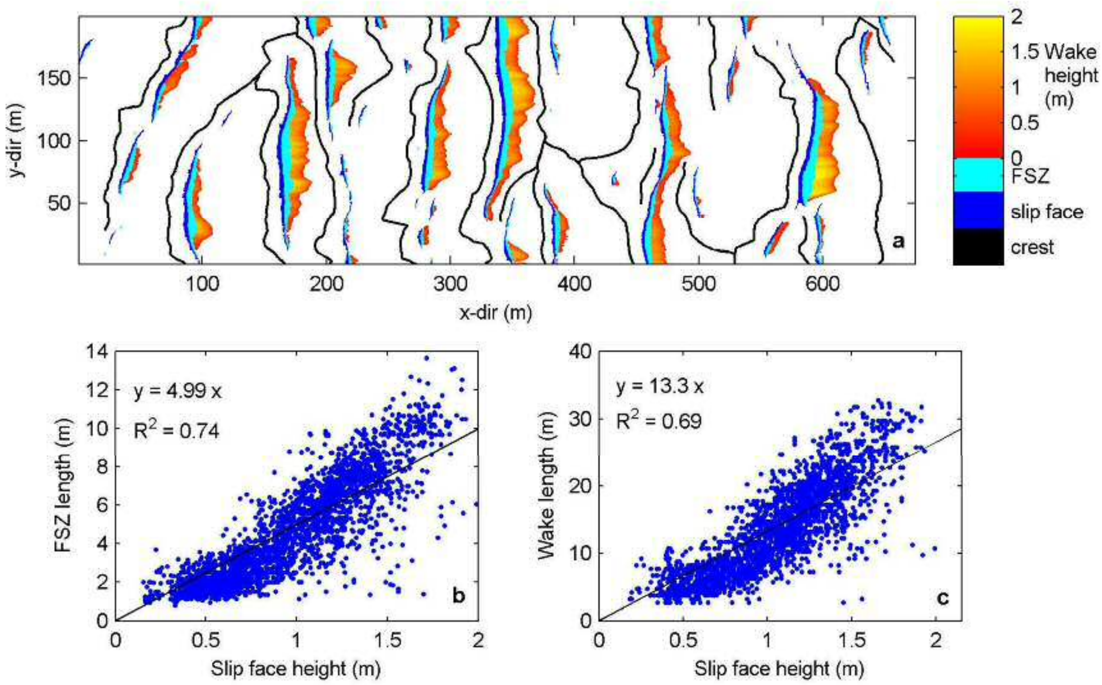

Figure 2. (a) position the crest lines, slip faces and flow separation zone (FSZ) and height of the wake (vertical distance between the lowest and highest point of the wake) across the model domain, flow is from left to right; (b) flow separation zone length as a function of slip face height and (c) wake length as a function of slip face height.

However, the direction of the slip face compared to the flow does not seem to have a strong effect on the presence of a turbulent wake. A wake is therefore predicted to form behind slip faces with a height greater than 0.6 m and maximum angle steeper than 20°.

4 CONCLUSIONS

A three-dimensional numerical model was used over a bedform field from the Rio Paraná to bring insights in the relation between complex 3D bed morphology and flow properties. The main conclusions of this work are:

- The presence and size of the flow separation zone and turbulent wake depends on the presence and properties of the slip face (lee side angles >15°) and not on those of the crest.

- A flow separation zone forms preferably over steep and high slip faces with a direction transverse to the flow; the flow separation length can be estimated as being 5 times the height of the slip face.

- A wake develops over steep and high slip faces, with only little influence of the slip face direction. The length of the wake is around 13 times the slip face height.

A detailed description of the bedform morphology including the presence and properties of the slip face is therefore necessary to correctly represent the complex interaction of flow and bedform.

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6 REFERENCES

Allen, J.R.L. 1968. Current Ripples. New York, NY.

Best, J., 2005. The fluid dynamics of river dunes: A review and some future research directions. Journal of Geophysical Research 110, 21. doi:10.1029/2004JF000218

Deltares. 2014. User Manual Delft3D-FLOW. Delft, The Netherlands.

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, 57-69. doi:10.1016/j.csr.2014.09.001

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, 986-1005. doi:10.1002/2013WR014587

Lefebvre, A., Paarlberg, A.J. and Winter, C., 2016. Characterising natural bedform morphology and its influence on flow. Geo-Marine Letters 36, 379–393. doi:10.1007/s00367-016-0455-5

Lefebvre, A. and Winter, C., 2016. Predicting bed form roughness: the influence of lee side angle. Geo-Marine Letters 36, 121-133. doi:10.1007/s00367-016-0436-8

Maddux, T.B., Nelson, J.M. and McLean, S.R., 2003. Turbulent flow over three-dimensional dunes: 1. Free surface and flow response. Journal of Geophysical Research: Earth Surface 108, doi:10.1029/2003JF000017

Omidyeganeh, M. and Piomelli, U., 2013. Large-eddy simulation of three-dimensional dunes in a steady, unidirectional flow. Part 1. Turbulence statistics. Journal of Fluid Mechanics 721, doi:10.1017/jfm.2013.36

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, F04S03. doi:doi:10.1029/2004JF000231

Rubin, D.M., 2012. A unifying model for planform straightness of ripples and dunes in air and water. Earth-Science Reviews 113, 176-185. doi:10.1016/j.earscirev.2012.03.010

Venditti, J.G., 2007. Turbulent flow and drag over fixed two- and three-dimensional dunes. Journal of Geophysical Research 112, F04008. doi:10.1029/2006JF000650