The influence of lee side shape on flow above bedforms

A. Lefebvre *MARUM - University of Bremen, Bremen, Germany – alefebvre@marum.de*
J. Cisneros *the University of Texas at Austin, Austin, USA – jcisneros1024@gmail.com*

ABSTRACT: Underwater dunes have a diversity of morphology, ranging from low to high-angle lee sides, and sharp or rounded crests. We carried out a large number of numerical simulations of flow over dunes with a variety of morphologies to investigate the influence of lee side morphology on flow properties. Our results show that the value of the mean lee side angle and the value and position of the maximum lee side angle have an influence on the flow properties investigated. We propose a classification with 3 types of dunes: (1) low-angle dunes (mean lee side < 10°), over which there is generally no permanent flow separation; (2) intermediate-angle dunes (mean lee side 10-20°) over which there is likely an intermittent flow separation; and (3) high-angle dunes (mean lee side >20°) over which the flow separates at the brink point and reattaches shortly after the trough, and over which turbulence is high.

1 INTRODUCTION

Until recently, most studies focussed on so-called "high-angle dunes" which possess a steep lee side with slopes of around 30°. These dunes commonly form in small rivers and in flumes (Van der Mark et al., 2008). Over such dunes, flow separation and recirculation over the lee side produces a turbulent wake and induces bedform roughness. However, many dunes have recently been observed to be "low-angle dunes" with lee side angles much lower than the angle-of-repose. Over low-angle dunes, flow separation is absent or intermittent, and turbulence and roughness are lower than over high-angle dunes (Kwoll et al., 2016, Lefebvre and Winter, 2016). In large rivers, mean lee side angles are commonly between 5° and 20° (Cisneros et al., 2020) as illustrated in Figure 1 by data from the Mississippi and Waal Rivers. Bedform lee sides in tidal environments are also often low, with, for example in the Weser Estuary, typical values of 5 to 20° (Lefebvre et al., 2021, Figure 1).

In addition, contrary to previous simplifications of lee side shape, the lee side is rarely a straight line but rather made of several steeply and gently sloping portions. Typically, a comparatively steep slope is observed somewhere along the lee side with gentler slopes towards the crest and/or the trough. In large rivers, the maximum lee side angle is on average 20.5° (Cisneros et al., 2020). In constrained tidal environments (e.g. estuaries and tidal inlets), maximum lee side angles are usually less than 20° (Dalrymple and Rhodes, 1995, Lefebvre et al., 2021, Prokocki et al., 2022) (Figure 1c). It is likely that marine dunes (i.e. dunes found in open marine environments such as continental shelves) have a variety of mean and maximum lee side angles. In any case, it should be noted that in tidal environments, flow reverses from one tidal phase to the next. However large dunes usually stay oriented in one direction during the whole tidal cycle. Therefore, lee sides may be steep during one tidal phase but gentle during the following tidal phase.

Interestingly, the shape of river and estuarine dunes differs. River dunes have their steepest slope close to the trough and a rounded crest (Cisneros et al., 2020), whereas estuarine dunes have their steepest slope close to the crest and a sharp crest (Dalrymple and Rhodes, 1995; Lefebvre et al., 2021). In open marine environments, various morphologies are found, from sharp to round crests (Van Landeghem et al., 2009, Zhang et al., 2019). Therefore, the difference in dune shape is not strictly reflecting differences between river and tidal environments, but rather the complex interaction between dune morphology, sediment properties and hydrodynamics.

The influence of the lee side morphology and how it fits within the coupling of feedbacks in the morphodynamic triad has not yet been systematically studied. The aim of this work is therefore to characterise flow properties (velocities and turbulence) over low and high-angle dunes with their steepest slope close to the crest and close to the trough using numerical experiments.

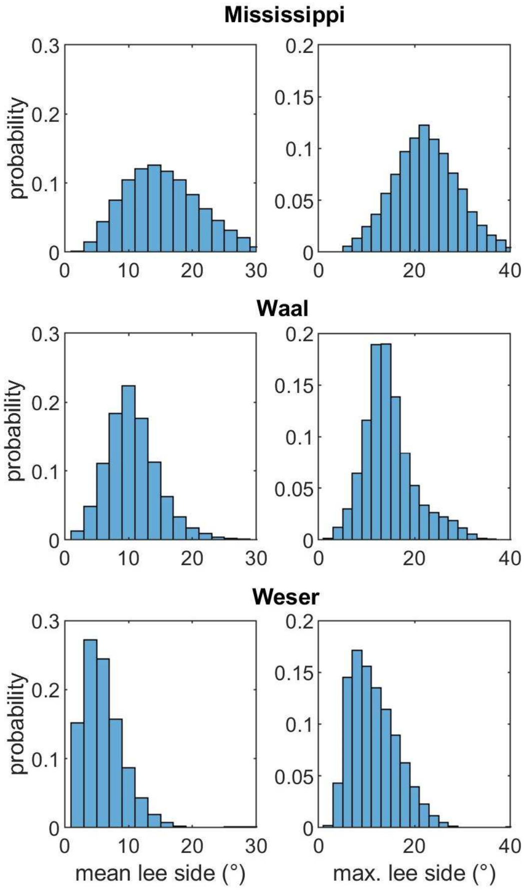

Figure 1. Mean and maximum lee side angles from dunes found in the Mississippi and Waal Rivers (data from Cisneros et al., 2020) and the Weser Estuary (Data from Lefebvre et al., 2021).

2 METHODS

2.1 Model description

Numerical experiments were carried out using Delft3D (Deltares, 2014), a process-based open-source integrated flow and transport modelling system. In order to capture non-hydrostatic flow phenomena such as flow separation and recirculation on the lee of dunes, the non-hydrostatic pressure can be computed.

The Delft3D modelling system has been used to setup a two-dimensional vertical (2DV) numerical model using the non-hydrostatic pressure correction technique to simulate horizontal and vertical velocities and turbulent kinetic energy (TKE) above fixed bedforms. The model has been previously calibrated, validated and verified (Lefebvre et al., 2014a, Lefebvre et al., 2014b). The simulations were performed on a 2DV plane Cartesian model grid over a fixed bed (i.e. no sediment transport) composed of 10 similar bedforms. The following conditions were prescribed constant in time at the lateral open boundaries of the model domain: a logarithmic velocity profile at the upstream boundary, and a water surface elevation of 0 m at the downstream boundary. The bed roughness was set as a uniform roughness length $z_0 = 0.0001$ m. The dune height and length, the water depth and the vertical and horizontal grid size were kept similar for all simulations. The horizontal grid size was set as dx = 0.09 m (271 grid point per dune). A non-uniform vertical grid size, stretched in the vertical direction with fine spacing near the bed and coarser spacing in the water column, was used.

2.2 Model experiments

A total of 88 simulations were carried out to test the influence of lee side morphology on flow velocities and turbulent kinetic energy. For all simulations, bedform height ($H_b = 0.89$ m) and length ($L_b = 24.4$ m), water depth (h = 8 m) and mean flow velocity (0.8 m/s) were kept similar. The stoss side followed a cosine shape and the lee side was made of either a line (straight lee side) or three lines (complex lee side). The straight

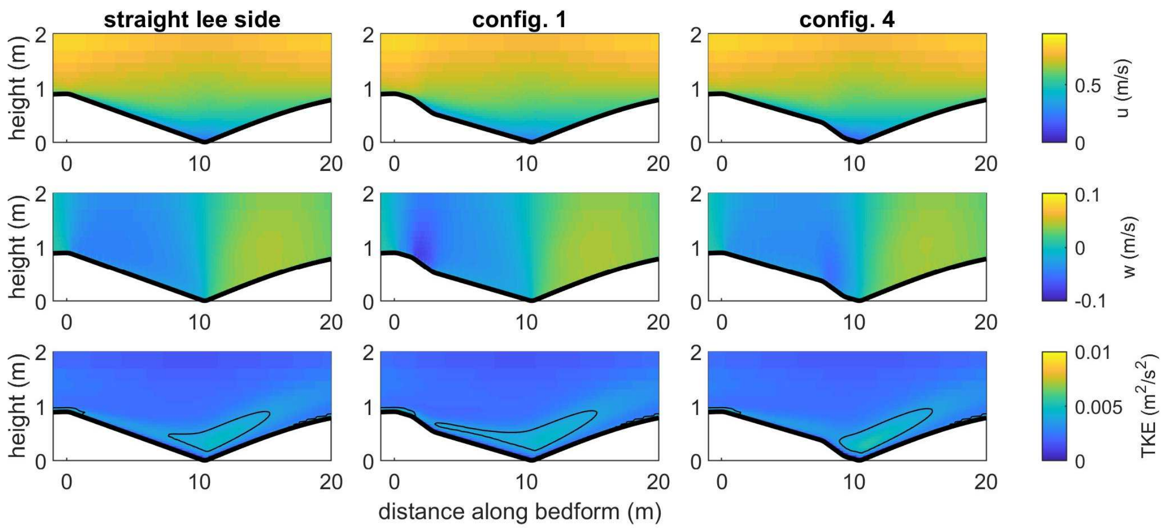

Figure 2. Horizontal streamwise velocity (u), vertical velocity (w) and turbulent kinetic energy (TKE) over dunes with mean lee side of 5°, a straight lee side (left panel), a max lee side angle of 10° situated close to the crest (config. 1, middle panel) and close to the trough (config. 4 right panel)

lee side experiments were made with lee side angles varying from 5° to 30°, in increments of 5°. For each mean lee side angle, simulations were done with the lee side composed of three segments: a steep portion where the maximum angle was fixed and upper and lower lee sides which had angles adjusted so that the mean angle would be between 5 and 30°, in increments of 5°. The steep portion height was one third of the bedform height. For each maximum lee side angle, four configurations were tested, with the position of the steep portion varying from close to the crest to close to the trough.

2.3 Model output analysis

From the simulation results, the horizontal and vertical velocities and the TKE above the 7^{th} bedform (from a total of 10 bedforms) were investigated. The position and size of the flow separation zone, when present, was calculated as the region in which the flow going upstream (i.e. negative horizontal velocity) is compensated by flow going downstream. Because Delft3D uses the Reynolds-averaged Navier–Stokes equations, it was not possible to model intermittent flow separation zone; only permanent flow separation can be simulated and was considered here. The mean and maximum TKE over the 7^{th} bedform were computed as indicators of the overall turbulence produced and dissipated over each dune shape. The turbulent wake was defined as the region where TKE is more than twice the average TKE above a flat bed with similar hydrodynamic conditions.

3 RESULTS

Based on our results, it is useful to make a distinction between low-angle, intermediate-angle and high-angle dunes.

3.1 Low-angle dunes

Flow and turbulence patterns over low-angle dunes (mean lee side < 10°) are illustrated by Figure 2, which shows dunes with a mean lee side of around 5° and a maximum angle of 10°, the most common configuration in the Weser Estuary. As typically observed over dunes, the horizontal velocity is highest above the crest and lowest above the trough. Vertical velocity shows flow going downwards above the lee side, with the strongest downward flow observed above the steep portion, and flow going upwards above the stoss side. There is generally no flow separation except if the

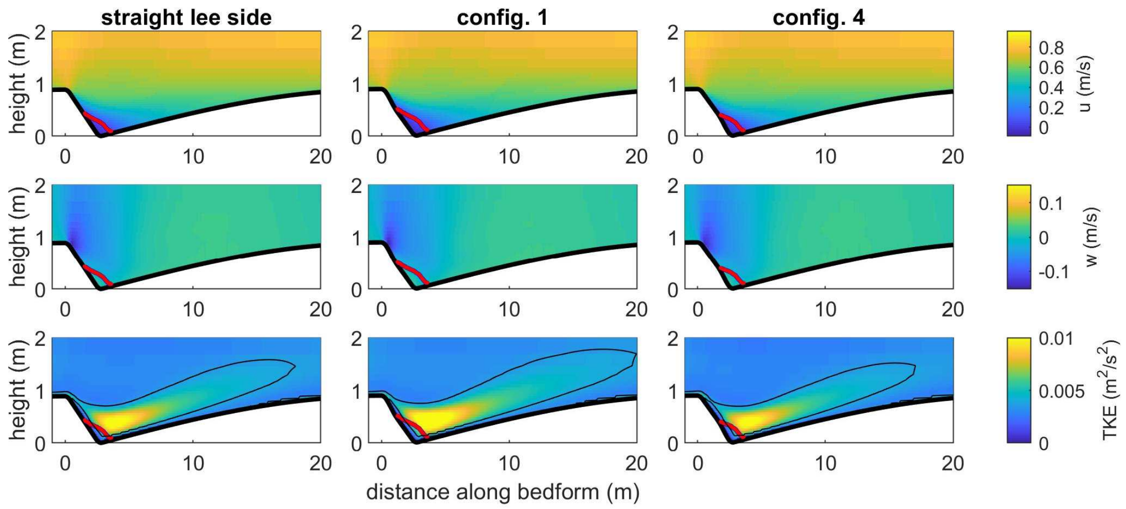

Figure 3. Horizontal streamwise velocity (u), vertical velocity (w) and turbulent kinetic energy (TKE) over dunes with mean lee side of 20°, a straight lee side (left panel), a max lee side angle of 25° situated close to the crest (config. 1, middle panel) and close to the trough (config. 4 right panel)

steep portion is at least 20° and situated close to the trough. However, it should be noted that this type of dunes (with a mean lee side angle < 10° and maximum angle > 20°) is not commonly observed. The turbulent wake generally starts over the steep portion and extends downstream down to a distance of ca. 5 m after the trough. Therefore, although the mean and maximum TKE are strongest for steep portions closest to the trough, the turbulent wake is longest for steep portions close to the crest (Figure 2).

3.2 Intermediate-angle dunes

Flow over intermediate-angle dunes (defined here as mean lee side angles between 10° and 20°) is difficult to correctly characterise from the results of our simulations. No systematic variations in flow separation zone and turbulent wake properties with mean and maximum angles could be established. This is likely because over intermediate-angle dunes, these properties are time-dependant. For example, flow separation is likely to be intermittent. As time-dependency is not resolved in the model we used, it is difficult to draw conclusions from our results. We suggest that these dunes should be investigated with laboratory experiments, field measurements and Reynolds-resolving models in order to precisely characterise time-dependant flow properties.

3.3 High-angle dunes

Over high-angle dunes (defined here as mean lee side angles over 20°), a flow separation is always observed. The flow generally separates over the steep portion and reattaches shortly after the trough (Figure 3). As a result, flow separation is longer for maximum angles situated close to the crest than for those situated close to the trough. The highest downward velocity is always situated just after the crest, independently of the maximum angle position. Significant differences are observed for the turbulent wake: it is especially strong (i.e. high TKE intensity) and spatially developed for steep portions close to the crest. As the position of the steep portion is getting closer to the trough, the turbulent wake decreases in size and intensity.

4 DISCUSSION

Our results show that the mean lee side angle has the strongest control over flow separation and turbulence over dunes, with a secondary influence of the position and value of the maximum lee side angle. We propose a distinction between three types of dune: low-angle dunes, intermediate-angle dunes and high-angle dunes. This differs from most classifications which recognise only high and low-angle dunes but not intermediate (Best, 2005, Kostaschuk and Venditti, 2019, Venditti, 2013). We base our classification between low, intermediate and high-angle dunes on flow properties investigated in the present study, but also on flow properties and sediment dynamics from previous research. Properties of each dune category can be identified. Over low-angle dunes (mean lee side < 10°), there is no flow separation, except if a very steep portion (slope > 20°) is found. Low-angle dunes generate little turbulence and are likely to induce little bedform roughness (Lefebvre and Winter, 2016; Kwoll et al., 2016). Over intermediate dunes (mean lee side angles between 10° and 20°), flow separation is intermittent (Kwoll et al., 2016). Turbulence and roughness are intermediate between low and high-angle dunes. No pattern can be found between the position of the maximum angle and flow properties. Our results show the limitations of studying intermediate dunes with Reynolds-averaged models such as Delft3D. Over high-angle dunes (mean lee side > 20°), a developing to fully-developed flow separation is present, a strong turbulent flow is observed and a high bedform roughness is created. If the maximum angle is close to the crest, flow separation is longer and the turbulent wake is stronger than if the maximum angle is close to the trough.

This distinction between low, intermediate and high-angle dunes is important for a range of processes such as the evaluation of bed roughness, understanding the relation between hydrodynamics, sediment transport and dune morphology, how dunes are identified in the depositional record, and unravelling the controlling processes leading to different lee side angle slopes and shapes.

5 CONCLUSIONS

Numerical simulations were carried out in order to estimate the influence of the value and position of the maximum lee side angle on flow above dunes with varied mean lee side slopes. Based on our results and previous literature, we propose a distinction between three types of dunes:

- Low-angle dunes, with mean lee side lower than 10°. Over such dunes, there is generally no permanent flow separation. The turbulent wake is weak, but strongest and most contained (limited spatial extent) for steep maximum angles situated close to the trough.
- Intermediate-angle dunes, with mean lee side of 10 to 20°. Over such dunes, there is rarely a permanent flow separation but it is likely that an intermittent flow separation forms. When present, flow separation is observed over the trough, independently of the maximum lee side angle position.
- High-angle dunes, with mean lee side of more than 20°. Over such dunes, the flow separates at the brink point and therefore, flow separation is longest if the maximum angle is close to the crest. The turbulent wake is strong, strongest and most extended for steep maximum slopes situated close to the crest.

This classification is more specific than previous classification, which only introduced low and high-angle dunes, and describes the specifics of flow properties depending on lee side morphology. It allows for a precise consideration of the interaction between dune morphology and flow. To correctly take this interaction and its consequences into account, detailed reports of dune morphology from varied environments are needed.

6 ACKNOWLEDGEMENT

Alice Lefebvre is funded through the Cluster of Excellence ‘The Ocean Floor – Earth’s Uncharted Interface’.

7 REFERENCES

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

Cisneros, J., Best, J., van Dijk, T., de Almeida, R.P., Amsler, M., Boldt, J., Freitas, B., Galeazzi, C., Huizinga, R., Ianniruberto, M., Ma, H.B., Nittrouer, J.A., Oberg, K., Orfeo, O., Parsons, D., Szupiany, R., Wang, P., Zhang, Y.F., 2020. Dunes in the world's big rivers are characterized by low-angle lee-side slopes and a complex shape. Nature Geoscience 13, 156-+. https://doi.org/10.1038/s41561-019-0511-7

Dalrymple, R.W., Rhodes, R.N., 1995. Chapter 13 Estuarine Dunes and Bars, in Developments in Sedimentology. Elsevier, 359-422

Deltares, 2014. User Manual Delft3D-FLOW. Deltares,

Kostaschuk, R.A., Venditti, J.G., 2019. Why do large, deep rivers have low-angle dune beds? Geology 47, 919-922. https://doi.org/10.1130/g46460.1

Kwoll, E., Venditti, J.G., Bradley, R.W., Winter, C., 2016. Flow structure and resistance over subaquaeous high- and low-angle dunes. Journal of Geophysical Research: Earth Surface 121, 545-564. https://doi.org/10.1002/2015JF003637

Lefebvre, A., Herrling, G., Becker, M., Zorndt, A., Krämer, K., Winter, C., 2021. Morphology of estuarine bedforms, Weser Estuary, Germany. Earth Surface Processes and Landforms https://doi.org/10.1002/esp.5243

Lefebvre, A., Paarlberg, A.J., Ernstsen, V.B., Winter, C., 2014a. Flow separation and roughness lengths over large bedforms in a tidal environment: a numerical investigation. Continental Shelf Research 91, 57-69. https://doi.org/10.1016/j.csr.2014.09.001

Lefebvre, A., Paarlberg, A.J., Winter, C., 2014b. Flow separation and shear stress over angle of repose bedforms: a numerical investigation. Water Resources Research 50, 986-1005. https://doi.org/10.1002/2013WR014587

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

Prokocki, E.W., Best, J.L., Perillo, M.M., Ashworth, P.J., Parsons, D.R., Sambrook Smith, G.H., Nicholas, A.P., Simpson, C.J., 2022. The morphology of fluvial-tidal dunes: Lower Columbia River, Oregon/Washington, USA. Earth Surface Processes and Landforms 47, 2079-2106. https://doi.org/10.1002/esp.5364

Van der Mark, C.F., Blom, A., Hulsher, S.J.M.H., 2008. Quantification of variability in bedform geometry. Journal of Geophysical Research 113, F03020. https://doi.org/10.1029/2007JF000940

Van Landeghem, K.J.J., Wheeler, A.J., Mitchell, N.C., Sutton, G., 2009. Variations in sediment wave dimensions across the tidally dominated Irish Sea, NW Europe. Marine Geology 263, 108-119. https://doi.org/10.1016/j.margeo.2009.04.003

Venditti, J.G., 2013. Bedforms in sand-bedded rivers, in Treatise on Geomorphology. Academic Press, 137-162

Zhang, H., Ma, X., Zhuang, L., Yan, J., 2019. Sand waves near the shelf break of the northern South China Sea: morphology and recent mobility. Geo-Marine Letters 39, 19-36. https://doi.org/10.1007/s00367-018-0557-3