Characterisation of flow dynamics over estuarine bedforms: An experimental approach

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ABSTRACT: In many estuaries, large bedform fields develop due to the strong hydrodynamics and high availability of sandy sediment. Flow above these bedform fields differs fundamentally from unidirectional flow above well-known angle-of-repose (30° slope) triangular bedforms which until now have been the focus of laboratory and numerical modelling studies. Estuarine bedforms are mainly low-angle dunes, with mean lee slopes of 5 to 20°. Flow properties over such gentle slopes are currently not precisely characterised. To address this, this study aims at characterising flow properties over estuarine bedforms through flume experiments and numerical simulations. A series of experiments will be carried out in a large flume facility at the BAW in Hamburg, Germany and high-resolution numerical simulations of flow over three-dimensional bedform fields will complement the flume experiments.

1 INTRODUCTION

Traditionally, the effect that bedforms have on the flow has been investigated over two-dimensional (2D) bedforms having an angle-of-repose (30°) lee side and a triangular shape. These bedforms are representative of dunes observed in flumes and small rivers. Over such bedforms, the flow separates at the crest and recirculates over the steep lee side. A turbulent wake develops along the shear layer between the separated and overlying flow and dissipates downstream (Kwoll et al., 2016). Such bedform generates a high form roughness which can be several orders of magnitude stronger than the grain roughness (Van Rijn, 1984). Therefore, they constitute a major factor in the calculation and prediction of hydrodynamics and sediment transport. Recently, it has been demonstrated that in large rivers, bedforms are mainly low-angle dunes with an average lee side slope of around 10° (Cisneros et al., 2020). Although river dunes are mainly low-angle, the flow above such low-angle bedforms has until now received little attention. This is also the case for estuarine dunes found at the confluence of river mouth and sea.

Bedforms have been observed in various estuaries around the world. Dalrymple and Rhodes (1995) give a thorough review of the early work related to estuarine bedform dynamics, with a focus on bedforms found in the outer, marine-dominated part of estuaries. In tidal environments, flow reverses from one tidal phase to the next. Therefore, the positions of the stoss and lee sides switch during a tidal cycle. Similar to bedforms found in large rivers, the shape of tidal bedforms is thought to control flow separation, turbulent wake and, therefore, bedform roughness and sediment transport. Bedforms found in estuarine and tidal environments have been reported to have mean lee sides angles smaller than the angle-of-repose, however, portions of the lee sides as steep as 25-30° suggest that flow separation may happen over restricted portions of the lee slope (Aliotta and Perillo, 1987, Lefebvre et al., 2013). On the contrary to river bedforms, estuarine bedforms have their steepest slope situated close to the crest (Fenster et al., 1990, Dalrymple and Rhodes, 1995, Lefebvre et al., 2021). Until now, bedforms with such a shape have not been systematically studied and it is unknown how flow properties over estuarine bedforms differ to that over river bedforms. Furthermore, estuarine bedforms found in nature are three-dimensional with sinuous crestlines and irregular dimensions. The influence of crestline sinuosity on unidirectional flow has been documented (Maddux et al., 2003, Venditti, 2007, Lefebvre, 2019). However, it has not been specifically investigated yet in tidal environments where flow reversal affects the relation between hydrodynamics and morphology. With this, it is also necessary to characterise the flow properties over natural estuarine bedforms where an effect of flow reversal is expected to occur.

2 OBJECTIVES OF THE STUDY

This study further characterises the flow dynamics above estuarine bedforms. This objective is accomplished with two experimental approaches:

(1) High-resolution measurements of flow above representative estuarine bedforms.

For this, physical experiments will be carried out in the flume at Federal Waterways Engineering and Research Institute (BAW) Hamburg. Each experiment will investigate flow properties (flow velocities, turbulence, turbulence structures) above a set of representative estuarine bedforms, whose shapes were chosen to represent the range of bedform geometries observed in the Weser Estuary.

(2) Numerical simulations of flow properties (mean flow and turbulence) above a natural estuarine bedform field.

Numerical simulations will be carried out over a natural bedform field to complement the flume experiments. The numerical simulations will focus on the effect of three-dimensionality and natural estuarine morphology on tidal flows.

This study is significant for a wide range of fundamental and applied research in shallow and deep water. Most of the knowledge of flow properties has been acquired above simplified angle-of-repose bedforms. This knowledge, however, is likely not transferable to flow properties above natural low to very low angle dunes. The results of this present study can be used to better predict the interaction between bedforms, flow and sediment movement in estuaries.

3 PLANNED EXPERIMENTS

3.1. Flume experiments

Laboratory experiments will be conducted at the facilities of BAW Hamburg. The experimental flume is a recirculating flume consisting of two straight sections connected at their respective ends by a semi-circular area to form a closed recirculating channel. The total length of the flow channel is 220 m in which the above ground channel section has a length of 80 m, width of 1.5 m and a maximum water depth of 1 m. A maximum flow velocity of 1 m/s can be generated in two opposite directions.

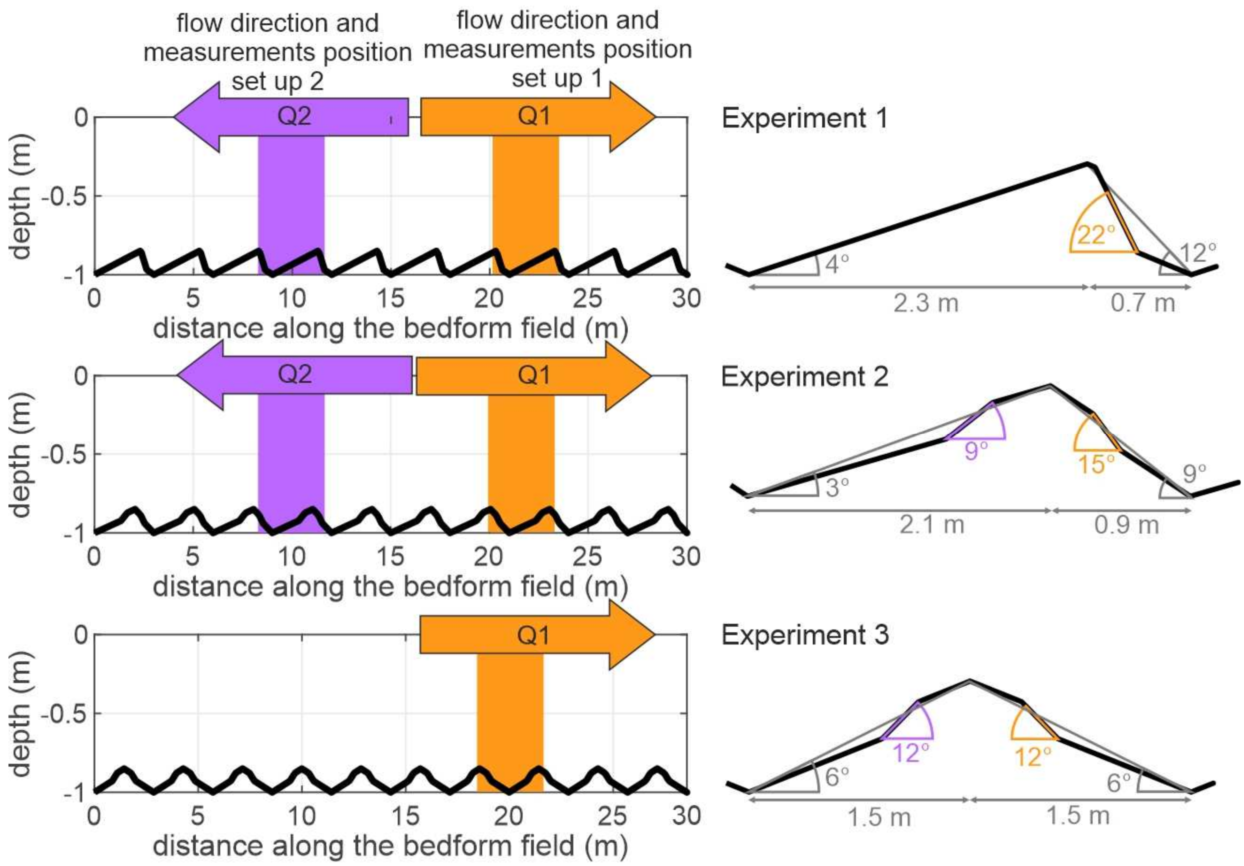

Figure 1. Experimental design of the flume experiments

For all the experiments, a set of 10 prototype bedforms will be installed in the flume to represent a bedform field. The dimensions of the bedforms are based on bedform characteristics as measured from the bathymetry data of the Weser Estuary (Lefebvre et al., 2021). To allow comparison between experiments, mean water depth, bedform length and height are kept constant for all the experiments and only the shape of the bedform is changed. Importantly, the position of the steepest part of the bedform sides will be close to the crest to mimic the shape of a natural estuarine and marine bedform (Figure 1). The dimensions of the bedforms are scaled down by a factor of 15 compared to field measurements.

A high-resolution flow measurement is conducted for all the three experiments using an acoustic device above the 7th bedform (Figure 1) where the flow is already fully adapted to the bedform field. For all three experiments hydrodynamic quantities will be investigated including the mean streamwise and vertical flow velocities to define the zone of permanent flow separation, the turbulent kinetic energy (TKE) to define the turbulent wake, the intermittency factor (IF, percentage of the measured time series at one point occupied by the reversed flow) to define the zone of temporary flow separation and the vertical gradient of the time-averaged streamwise velocity to define the zone of the shear layer.

The novelty of these high-resolution flow measurements compared to previous studies is that the investigated bedform shapes will be representative of estuarine bedforms and not triangular or river bedforms. It will be the first time that flow will be measured in detail over very low angle dunes. A variety of maximum lee side slopes will be investigated (9°, 12°, 15° and 22°). These include the slopes where flow separation is changing from absent to intermittent to permanent. Since the bedforms are relatively large compared to other flume experiments,

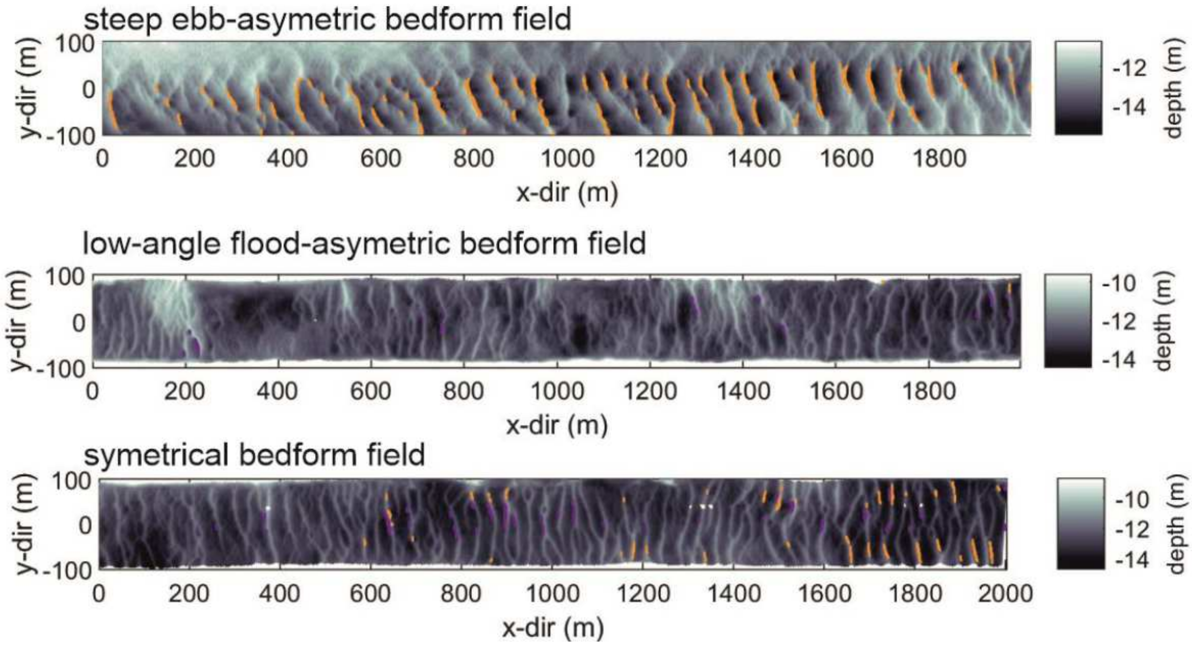

Figure 2. Bathymetry of proposed numerical simulations; violet: flood steep faces, orange: ebb steep faces

measurements can be taken close to bed and even a small flow separation can be detected.

3.2. Numerical modelling

In addition to the flume experiments, numerical modelling will be carried out to address the effects of three dimensionality and bedform sinuosity which are not captured in the prototype bedforms due to scaling issues typically encountered in a physical experiment. The numerical modelling will be done using the DELFT-3D model with bathymetry data based on the Weser Estuary with a grid resolution of 2 m (Lefebvre et al., 2021).

Three straight sections, about 2-3 km long and 200 m wide (Figure 2), will be investigated: (1) bedform field with steep ebb-oriented dunes; (2) bedform field with low-angle flood-oriented dunes; (3) bedform field with symmetrical dunes. These bedform fields were chosen both to represent the variety of bedforms observed in the Weser Estuary and to study similar morphologies already investigated in the flume (i.e., steep asymmetric, asymmetric, and symmetric bedforms in the estuary) to complement the physical experiments.

For each section, two simulations will be carried out, each with the current velocity imposed in opposing direction, in order to model the ebb and flood phases. This setup will allow to investigate the differences and properties of flow separation and turbulence depending on bedform orientation compared to the flow direction.

Numerical outputs at the end of simulation include the horizontal (U, V) and vertical (W) velocities and TKE. As a first step for the numerical analysis, the depth-, streamwise- (U) and cross- (V) averaged flow properties can be examined in order to provide an overview of the effect of the 3D morphology on averaged flow properties. Next, the presence and size of the flow separation zone (i.e. the region in which the flow going upstream is compensated by the flow going downstream), the shear layer (i.e. the steep portion of the mean velocity gradient which shows a change in velocity between the regions within and above the flow separation zone), the turbulent wake (i.e. the zone of high TKE) and the secondary circulation (i.e. the zones with strong crosswise flow velocity) will be investigated. Furthermore, bed shear stress along the bedform fields will allow to investigate the local effects of bedforms on flow and, thus, predict sediment transport pathways. These quantities will then be compared to the bedform morphology.

Furthermore, the flume experiments will also be used to validate the model over low angle bedforms. For this case, numerical models can be set up at a flume scale and the results of the physical and numerical simulations can then be directly compared.

4 CONCLUSIONS

A detailed high-resolution experimental approach, both physical and numerical, is presented to characterise the flow dynamics over low angle estuarine bedforms. The proposed flume experiments are the first in which flow over very low angle dunes, resembling that of estuarine bedforms, will be measured in detail and in high-resolution owing to the large flume facility at BAW Hamburg.

Furthermore, a high-resolution numerical modelling using the DELFT-3D model is also proposed to complement the results of the flume experiments. Special attention is given to the three-dimensionality of the bedform to better represent the flow properties over bedform typically found in a natural tidal estuary.

This study aims to add to the present knowledge on flow dynamics over estuarine bedform which is, rather, not fully elaborated yet at present. Also, the results of this study may be utilized to better understand the mutual interaction among bedforms, flow and sediment movement in tidal estuary.

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