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Flow separation and roughness lengths over large bedforms in a tidal environment: A numerical investigation

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ABSTRACT

This study characterises the shape of the flow separation zone (FSZ) and wake region over large asymmetric bedforms under tidal flow conditions. High resolution bathymetry, flow velocity and turbulence data were measured along two parallel transects in a tidal channel covered with bedforms. The field data are used to verify the applicability of a numerical model for a systematic study using the Delft3D modelling system and test the model sensitivity to roughness length. Three experiments are then conducted to investigate how the FSZ size and wake extent vary depending on tidally-varying flow conditions, water levels and bathymetry. During the ebb, a large FSZ occurs over the steep lee side of each bedform. During the flood, no flow separation develops over the bedforms having a flat crest; however, a small FSZ is observed over the steepest part of the crest of some bedforms, where the slope is locally up to 15°. Over a given bedform morphology and constant water levels, no FSZ occurs for velocity magnitudes smaller than 0.1 m s^{-1}; as the flow accelerates, the FSZ reaches a stable size for velocity magnitudes greater than 0.4 m s^{-1}. The shape of the FSZ is not influenced by changes in water levels. On the other hand, variations in bed morphology, as recorded from the high-resolution bathymetry collected during the tidal cycle, influence the size and position of the FSZ: a FSZ develops only when the maximum lee side slope over a horizontal distance of 5 m is greater than 10°. The height and length of the wake region are related to the length of the FSZ. The total roughness along the transect lines is an order of magnitude larger during the ebb than during the flood due to flow direction in relation to bedform asymmetry: during the ebb, roughness is created by the large bedforms because a FSZ and wake develops over the steep lee side. The results add to the understanding of hydrodynamics of natural bedforms in a tidal environment and may be used to better parameterise small-scale processes in large-scale studies.

1. Introduction

In shallow water environments, the movement of sandy sediment under the action of currents and waves commonly generates rhythmic wavy features on the bed. The size and shape of these bedforms is usually considered to depend on hydrodynamic forcing, water depth and sediment size (Ashley, 1990). In estuaries, tidal inlets and rivers where the currents are strong and there is a high availability of sand, bedforms are commonly large, with a complex three-dimensional morphology involving crest line bifurcations and lateral variations of bedform dimensions, presence of superimposed bedforms and along and across-bedform sediment variations (Dalrymple and Rhodes, 1995). Furthermore, these bedforms usually present some degree of asymmetry (having both a gentle and a steep side, Fig. 1a). Flow over large asymmetric bedforms has been widely studied (see reviews by Best, 2005; Venditti, 2013). Bedforms exert a strong influence on the flow within what is here referred to as the "form-influenced flow field". Over asymmetric bedforms having a steep lee slope, this form-influenced flow field consist of a Flow Separation Zone (FSZ) and associated wake region (Fig. 1b). The FSZ is composed of a recirculating eddy generated by the strong pressure gradient over the bedform steep lee slope. A wake region, characterised by high turbulence intensities, grows along the upper boundary of the FSZ and extends downstream. The turbulence generated by the shear layer bounding the flow separation zone is dissipated in this region.

The resistance exerted by bedforms on the flow is generated within the form-influenced flow field through energy loss due to

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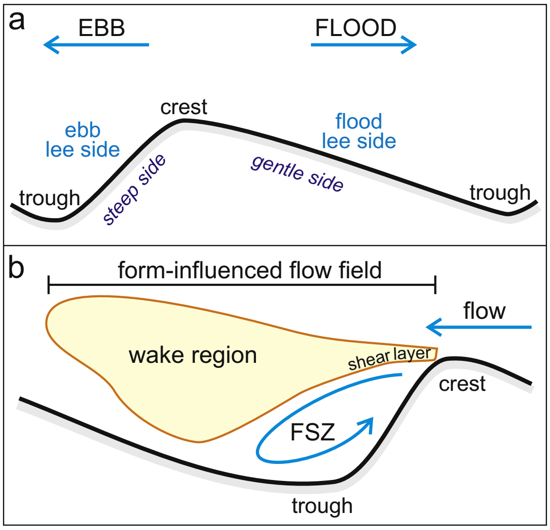

Fig. 1. (a) Nomenclature of asymmetric bedforms (here ebb-oriented) in a tidal environment and (b) detail of the form-influenced flow field (comprising the Flow Separation Zone (FSZ) and the wake region) during the ebb tidal phase.

turbulence in the wake region (Nezu and Nakagawa, 1993; Vanoni and Hwang, 1967). Furthermore, the form-influenced flow field is a region of complicated sediment transport patterns due to the presence of reverse flow within the FSZ, which alters the direction of bedload transport, and the generation of coherent flow structures along the shear layer, which controls the suspension of sand over large dunes (Kostaschuk, 2000; Kwoll et al., 2013; Venditti and Bennett, 2000). Therefore, a good knowledge of the dynamics of the form-influenced flow field is necessary for the understanding and modelling of hydro- and sediment dynamics in coastal environments where bedforms are present.

Bedforms with lee side angles close or equal to the angle-of-repose (~30°) commonly occur in unidirectional flow and the form-influenced flow field over such bedforms has been widely studied, especially through laboratory studies (Bennett and Best, 1995; Engel, 1981; Fernandez et al., 2006; McLean et al., 1999; Nelson et al., 1993; Venditti and Bennett, 2000). Over such bedforms, a permanent flow separation zone develops which results in an extended wake region showing high turbulence production and dissipation. However, bedforms with a lee side angle smaller than the angle-of-repose have also been observed in fluvial (e.g., Best and Kostaschuk, 2002) and tidal environments (e.g., Lefebvre et al., 2011b). The FSZ over lee sides gentler than the angle-of-repose is thought to be non-existent or intermittent. However, the exact slope at which the FSZ becomes permanent has not yet been determined. Paarlberg et al. (2009) assumed flow separation as permanent for slopes larger than 10°. Kostaschuk and Villard (1996) suggested that intermittent flow separation only occurs for lee side slopes smaller than 19°, and Best and Kostaschuk (2002) found that intermittent flow separation was present for about 4% of the time over bedforms with maximum lower lee side slopes of 14°.

Despite flow reversal in tidal environments, large bedforms usually maintain their asymmetry, typically being oriented with the residual flow direction (e.g. Bartholdy et al., 2002; Ernstsen et al., 2006). Therefore, lee sides may be steep or gentle depending on the tidal phase (Fig. 1a) which implies that the presence of a FSZ depends on flow direction (Lefebvre et al., 2013a). Furthermore, the angle of the steep side of tidal bedforms is often smaller than the angle-of-repose, typically between 10° and 20°, i.e., in the range of angles over which the presence of a permanent FSZ is still under debate. In addition, the influence of tidally-induced variations of flow velocity, water level and bathymetry on the form-influenced flow field is still to be determined; in other words, the effect on the FSZ and wake region of tidal flow acceleration and deceleration, tidal range and variations of bathymetry due to sediment movement during a tidal cycle remain to be understood.

It has been demonstrated that the presence or absence of a FSZ and associated wake region result in a change of hydraulic roughness, with the total flow resistance being an order of magnitude higher during the flow phase with steep lee sides, e.g. the ebb phase over ebb-oriented bedforms and vice versa (Hoitink et al., 2009; Lefebvre et al., 2011b, 2013a). Lefebvre et al. (2013a) assessed the presence of a FSZ together with estimates of total roughness along profiles covering large ebb-oriented bedforms in the Knudedyb tidal inlet (Danish Wadden Sea, North Sea). They concluded that the total hydraulic roughness was larger during the ebb, when there was evidence of a FSZ behind the large bedforms, than during the flood when no FSZ was detected over the bedforms gentle lee side. In that study the difficulty in measuring the near-bed flow and thus the evaluation of the presence and size of a FSZ in a natural environment was pointed out. Furthermore, turbulence along the transect lines could not be measured and the wake region could not be characterised. Another limitation of their study was the restriction due to flow acceleration/deceleration during the tidal cycle which reduced the amount of time during which the flow was steady enough to calculate reliable estimates of roughness. Recently it has been shown that numerical models can be used to simulate the interaction of bedforms and hydrodynamics (El Kheiashy et al., 2010; Lefebvre et al., 2014; Omidyeganeh and Piomelli, 2011; Stoesser et al., 2008). These may complement high-resolution measurements to compensate for limitations in field data as they allow simulations of near-bed flow fields, provide estimate of turbulence and can be used with tidal or steady boundary conditions.

Using numerical modelling, we aim at investigating the dynamic behaviour of the form-influenced flow field and roughness lengths over large bedforms during a tidal cycle. In this paper we will (1) characterise the shape of the FSZ and wake region over natural asymmetric bedforms during a tidal cycle, (2) analyse how the shape of the FSZ and wake region vary with changing flow velocities, water levels and bathymetry and (3) explain how bedform roughness varies during the tidal cycle and with the presence/absence of a FSZ.

2. Methods

2.1. Study area and field data

The Knudedyb tidal inlet channel, being ~8.5 km long and ~1 km wide and with an average water depth of ~15 m, connects a tidal basin of the Danish Wadden Sea to the adjacent North Sea. The tides in the area are semi diurnal with a tidal range of 1.6 m on average. The tidal inlet bed is sandy and covered with compound bedforms (Lefebvre et al., 2011a): large ebb-oriented bedforms (wavelengths of several hundred metres and heights of several metres) on which smaller bedforms (wavelengths of 3–5 m and heights of 0.15–0.3 m) are superimposed. These secondary bedforms reverse directions and migrate in the direction of the tidal currents while the primary bedforms stay ebb-oriented throughout the tidal cycle.

Repetitive ship-based surveys were conducted over two 700 m-long transect lines (Transect North and Transect South) crossing 3 and 4 primary bedforms (Fig. 2) with the RV Senckenberg on 17 October 2009 during a full tidal cycle (Lefebvre et al., 2013a). Flow velocity magnitudes and directions were measured using an acoustic Doppler current profiler (ADCP) operating at 1200 kHz