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Research papers

Estimation of roughness lengths and flow separation over compound bedforms in a natural-tidal inlet

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ABSTRACT

The hydraulic effect of asymmetric compound bedforms on tidal currents was assessed from field measurements of flow velocity in the Knudedyb tidal inlet, Denmark. Large asymmetric bedforms with smaller superimposed ones are a common feature of sandy shallow water environments and are known to act as hydraulic roughness elements in dependence with flow direction. The presence of a flow separation zone on the bedform lee was estimated through analysis of the measured velocity directions and the calculation of the flow separation line. The Law of the Wall was used to calculate roughness lengths and shear velocities from log–linear segments sought on transect-averaged and single-location velocity profiles. During the ebb tide a permanent flow separation zone was established over the steep (10–20°) lee sides of the ebb-oriented primary bedforms, which generated a consequent drag on the flow. During the flood, no flow separation was induced by the gentle (2°) lee side of the primary bedforms except over the steepest (10°) part of the lee side where a small separation zone was sometimes observed. As a result, hydraulic roughness was only due to the superimposed bedforms. The parameterized flow separation line was found to underestimate the length of the flow separation zone of the primary bedforms. A better estimation of the presence and shape of the flow separation zone over complex bedforms in a tidal environment still needs to be determined; in particular the relationship between flow separation zone and bedform geometry (asymmetry, relative height or slope of the lee side) is unclear. This would improve the prediction of complex bedform roughness in tidal flows.

1. Introduction

In sandy shallow water environments, the transport of sediment by currents and waves frequently generates rhythmic wavy features on the seabed. The size and shape of these bedforms is usually thought to depend on sediment size, water depth and hydrodynamic forcing (Ashley, 1990). In tidal inlets and rivers, the strong currents and the high availability of sandy sediment create bedforms that are frequently large, with lengths up to several tens of metres and heights of several metres (Buijsman and Ridderinkhof, 2008; Ernstsen et al., 2004; Idier et al.; van Santen et al., 2011). They commonly present a complex three-dimensional morphology with crestline bifurcations and lateral variations of bedform dimensions, presence of superimposed bedforms, along and across-bedform sediment variations and asymmetry (Dalrymple et al., 1995). Bedforms in tidal flows are here referred to as *tidal bedforms* and the names used to describe them are summarised in Fig. 1.

The bed morphology influences the overlying flow in the boundary layer, where the time-averaged current velocity profile ideally displays a logarithmic distribution above the bed and is commonly described by the von Kármán–Prandtl Law of the Wall

$$u(z) = \frac{u_*}{\kappa} \ln \frac{z}{z_0} \quad (1)$$

where u is the time-averaged current velocity at the height z above the bed, κ is the von Kármán constant (0.41), u_* is the shear velocity and z_0 (height z at which the current velocity is zero) is the roughness length. The Law of the Wall allows an indirect estimation of hydraulic roughness through the roughness length, which defines the frictional force that the bed exerts on the flow; other common measures of hydraulic roughness are the Nikuradse roughness length parameter k_s (for rough flow $z_0 = k_s/30$) and the drag coefficient C_D ($C_D = \kappa/\ln(z/z_0)$).

The Law of the Wall results from the momentum balance between the surface pressure gradient and the internal friction parameterized by a parabolic eddy viscosity assuming that the flow is steady, uniform and unstratified. However a tidal flow is

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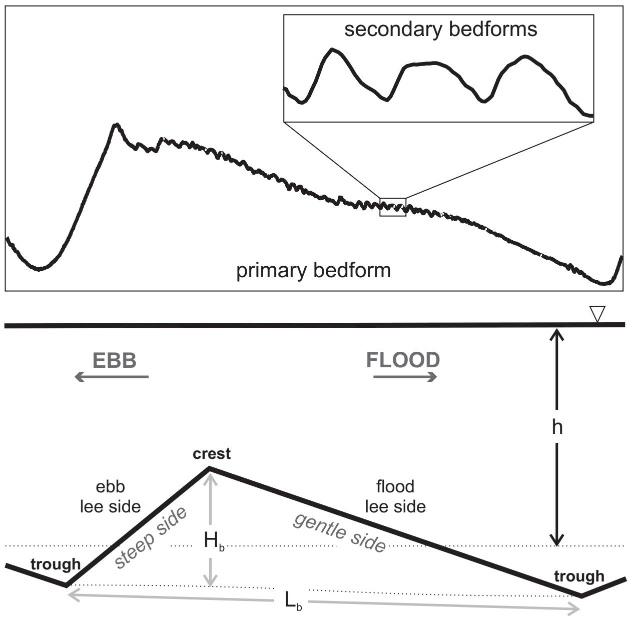

Fig. 1. Description of compound bedforms (upper panel) and names used to describe morphological and hydrodynamic characteristics of tidal bedforms (lower panel); H_b is the bedform height, L_b is the bedform length and h is the average water depth; in this case, the primary bedform is ebb-oriented.

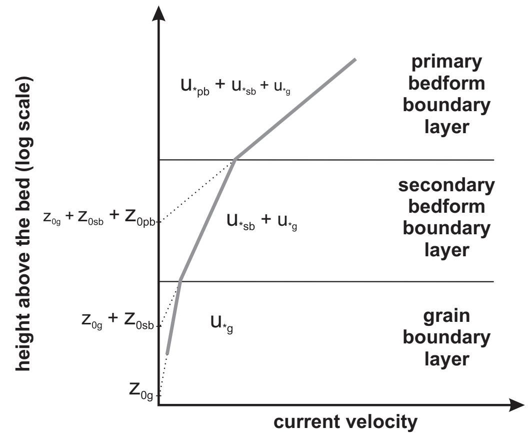

Fig. 2. Schematisation of a velocity profile over a bed with compound bedforms. The velocity profile is made up of different boundary layers controlling the different log–linear segments.

inevitably unsteady, often spatially non-uniform, and sometimes stratified, which limits the use of the Law of the Wall in tidal environments. Dyer (1986) identified six factors that may alter the shape of the logarithmic velocity profile: (1) acceleration or deceleration, i.e. flow unsteadiness; (2) variations in upstream roughness, i.e. flow non-uniformity; (3) bedforms; (4) stratification due to variations in temperature/salinity or suspended sediment concentration; (5) errors in determining the zero datum of the current meter array; and (6) surface wind waves and swell. We first assume that deviations from a simple logarithmic velocity profile are solely due to the presence of bedforms and other disturbances do not significantly affect the applicability of the Law of the Wall.

In case of a flat seabed, a grain boundary layer develops close to the bed and the increase of velocity as described by the Law of the Wall is linear with the logarithmic height above the seabed; the roughness length and associated friction velocity are controlled by the drag created by individual grains. When bedforms are present on the seabed, flow expansion on the bedform lee side leads to mechanical energy loss (Engelund and Fredsøe, 1982). Furthermore the sudden flow expansion creates a strong pressure gradient between the crest and the trough; when strong enough, the pressure gradient induces flow separation at the bedform crest and leads to the formation of a recirculation eddy in the flow separation zone (FSZ), causing further energy losses through turbulence (Vanoni and Hwang, 1967) resulting in the hydraulic bedform roughness (Dyer, 1986; Grant and Madsen, 1982). A secondary boundary layer associated with bedform friction is formed, extending further away from the seabed than the grain-related boundary layer; the increase of velocity with the logarithmic height above the seabed becomes segmented, with the highest segment (and associated z_0 and u_*) being controlled by the bedform roughness (Dyer, 1970; Kostaschuk and Villard, 1996). The shear velocity and roughness length associated with the bedform boundary layer are considerably larger than the roughness associated with the grain boundary layer. If several bedform populations are present (compound bedforms), several bedform-related boundary layers develop, each one extending to a certain height above the bed (Smith and McLean, 1977). The increase of velocity as described by the Law of the Wall becomes composed of several log–linear segments, each one related to the friction induced by one scale of roughness and representing a hierarchy of boundary layers (Fig. 2). Boundary layer characteristics can be calculated from the best-fit applied on the log–linear segments, the shear velocity being related to the slope of the best-fit line, and the roughness length to its y-intercept. Following this principle, earlier studies have described the influence of bedforms on the flow through analysis of the increase in velocity with height above the bed in a riverine environment (McLean, 1992; Smith and McLean, 1977; Villard and Kostaschuk, 1998) and in a tidal environment (Chriss and Caldwell, 1982; Dyer, 1970; Lefebvre et al., 2011a).

In rivers, the flow is unidirectional and overall steady (compared to tidal flows) and thus the bed topography is usually in equilibrium with the hydrodynamic conditions. In this environment bedforms are typically asymmetric with a steep lee slope, close or equal to the angle-of-repose (30°) over which a permanent FSZ develop (see review by Best (2005)). Recently however, symmetric low-angle bedforms (i.e. lee side angle $<10°$) were recognised to commonly occur in rivers; over these low-angle bedforms, intermittent or non-existent FSZ was recognised (Best, 2005). The occurrence of flow separation over steep (20 to 30°) and low-angle ($<10°$) bedforms is relatively well known. However, flow separation over bedform with intermediate-angles (10–20°) is still debated. The exact lee side slope at which flow separation will occur has not yet been determined: Paarlberg et al., 2009 considered that flow separation is permanent in time for a slope of 10° or more; Kostaschuk and Villard (1996) suggested that flow separation may occur intermittently only for lee side slopes up to 19°; and Best and Kostaschuk (2002) found that flow separation over bedforms with maximum lower lee side slope of 14° was present for about 4% of the time.

Bedform roughness is usually attributed to flow separation through transfer of mean flow energy to turbulent frequencies, leading to the dissipation of flow energy by viscous forces as heat (Nezu and Nakagawa, 1993). In rivers, flow separation is permanent over asymmetric bedforms with a steep lee side and therefore, bedform roughness is generally constant, except in case of abrupt change in flow conditions such as a flood (Paarlberg et al., 2010). Over intermediate and low angle bedforms, there is no permanent FSZ and turbulence is generated through intermittent separation or along the shear layer created by velocity gradients over the lee side flow expansion (Best and Kostaschuk, 2002). The roughness of low angle bedforms is less well known than those of

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