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Coupling bedform roughness and sediment grain-size sorting in modelling of tidal inlet incision

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ABSTRACT

A key problem in the decadal morphodynamic modelling of tidal inlet system is on the evolution of the inlet channels, especially the unrealistic channel incision. The present study attempts to couple two processes, including the bedform roughness and sediment grain-size sorting, in the two-dimensional, depth-averaged process-based model to solve the problem. Based on the comparison of the modelling results and relevant field observations in the Dutch Wadden Sea, it is suggested that bedform roughness height predictor is a useful tool for determining spatial and temporal heterogeneous bed frictions. Within tidal channels, bedform roughness is dominated by dune roughness. In order to represent "the memory of old bedforms", a relaxation time method was implemented. The corresponding large relaxation time (2 M2 tidal periods) smooths the tidal variations of dune roughness, and makes it respond to hydrodynamic changes on a longer time scale. When decadal morphological modelling is carried out, the model performance can be significantly improved by introducing either bedform (dune) roughness predictor or sediment sorting processes. The mechanisms are twofold. First, in the deep channels where flow velocities are high, large dunes develop and cause large bed drag coefficients. Second, coarser bed sediments within the channel area induced by sorting prevent the channel incision. If both effects are coupled in the morphodynamic modelling, the inlet channel incision is further controlled, which is not just a result of the linear superposition of both effects, because sorting can further promote the development of dunes within the deep channels.

1. Introduction

Tidal inlets and basins are important for economic, ecological and environmental reasons, e.g., by providing natural harbors, inland waterways, land resources, and marine invertebrates, fishes and birds (Reise, 2001; Anthony et al., 2009). To cope with the impacts of sea-level rise and human activities (e.g. land reclamation, harbor construction), a thorough understanding of the characteristics of tidal inlet morphodynamics is fundamentally necessary, so as to predict the morphological responses to these changes and to make appropriate decisions for management (Lee et al., 1999; van Goor et al., 2003; FitzGerald et al., 2008; Wang et al., 2012; van der Wegen, 2013).

Tidal inlets are complex dynamic systems, including a number of elements, e.g., inlet channels, flood-tidal deltas, ebb-tidal deltas, the adjacent beaches, dunes on barrier islands, and back-barrier tidal basins (de Swart and Zimmerman, 2009). Influenced by the external forces of tides, waves and currents, the dynamic behavior of tidal inlet evolution have been studied through process-based numerical modelling (Wang et al., 1995; Marciano et al., 2005; Dissanayake, 2011; Dastgheib, 2012; Yu et al., 2012, 2014; Wang et al., 2014a, 2014b).

Among the different aspects of the tidal inlet morphodynamics, the present study focuses on the problem of the incision of the main tidal channel. In decadal (~10^1 year or more) process-based models (van Maanen et al., 2016), the inlet development is often characterized by an unrealistic incision of the main tidal channel (Dissanayake, 2011; Dastgheib, 2012). In order to reduce the channel incision, several techniques have been adopted (van der Wegen, 2009): (1) increasing the effects of transverse bed slope transport to promote the stronger transverse downslope sediment transport; and (2) increasing the dry-cell erosion factor to stimulate bank erosion. In addition to the above methods, the effects including the spatial–temporal heterogeneous bedform roughness (Ganju and Sherwood, 2010) and bed sediment grain-size sorting (van der Wegen et al., 2011), are investigated in the present study.

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The total bed roughness consists of bedform roughness, skin (grain) roughness, and bed sediment motion roughness. The first part is the dominant component when bedforms develop (Smith and McLean, 1977; Xu and Wright, 1995). In the classification of van Rijn (2007a), with increasing dimensions, bedforms can be classified as ripples, mega-ripples, and dunes, which have typical roughness heights of 10^{-2} m, 10^{-2}–10^{-1} m, and 10^{-1}–10^{0} m, respectively. Bedform induced roughness is roughly proportional to sizes, especially the heights, and thus, dunes are the largest bedforms with the highest roughness. In tidal environments, because bedform size is related to grain size, water depth and flow velocity (Dalrymple et al., 1978; Ashley, 1990; Flemming, 2000; Bartholdy et al., 2002; Kubicki, 2008), the spatial–temporal heterogeneous sedimentologic and hydrodynamic environments result in the heterogeneities of bedform size and roughness. In deep tidal channels, due to coarse bed sediments, large water depth and strong current, large scale bedforms develop and dunes usually contribute as the major part of bedform roughness (Ernstsen et al., 2005; Buijsman and Ridderinkhof, 2008; Hughes et al., 2008; Barnard et al., 2013). For example, in the main tidal channel of the Marsdiep Inlet which is one of the inlets connecting Dutch Wadden Sea and the North Sea, observations show that dune heights range from 2 to 3 m. High dunes correspond to the deep trough of the channel, and the dune heights are larger than mega-ripple and ripple heights by at least an order of magnitude (Buijsman and Ridderinkhof, 2008). Bedform roughness heights can be estimated as a half of bedform heights (van Rijn, 2007a). Therefore, the bedform roughness heights reach up to 1.5 m and dominate the total bedform roughness, as well as the total roughness.

These large bedforms can pronouncedly increase the bed roughness, and then modify the sediment transport and morphological evolution (Tonnon et al., 2007). It is hypothesized that the elevated bed roughness is essential for the inlet channel development and is one of the key processes controlling the channel depth. The logic is that, the increases of water depth, bed sediment grain size, and current speed with respect to channel incision promote the bedforms (especially dunes) growth at the deep trough area, and the elevated bedform roughness enhances the flow drag and then prevents the incision at the trough area.

The bedform roughness predictor (e.g., van Rijn (2007a, 2007b)) can calculate bedform (roughness) height in terms of current speed, bed sediment grain size and water depth. For tidal environments, the tidal variations of current speed may result in the tidal variations of bedform (roughness) heights. However, field evidence suggests that, compared with mega-ripples and ripples, the dune shape and height, can keep relatively stable during a tidal cycle (Allen, 1978; McCave and Langhorne, 1982; Harris and Collins, 1984, 1985; Gao et al., 1994; Salvatierra et al., 2015). For instance, the observations of dune dynamics in an inlet channel of the Danish Wadden Sea suggested that the dune heights varied from 2.1 to 2.4 m during a tidal cycle (Ernstsen et al., 2006). Meanwhile, dune dimensions respond to the hydrodynamic changes in a longer time span (i.e., changes in tidal averaged and peak velocity) but with pronounced lags and reduced rates (Langhorne, 1982; Flemming and Davis, 1992). Thus the dune roughness predictor should be modified to adjust to tidal environments. A relaxation option is implemented in some coastal hydrodynamic and morphodynamic modelling systems (e.g., Delft3D), but how to parameterize the "relaxation time scale" cannot be found in the previous literatures.

The pioneering work of Teske (2013) involved the bedform dynamics into decadal morphological modelling of the Amelander Inlet, which is another inlet of the Dutch Wadden Sea. Bedform roughness heights were simulated using van Rijn (2007a)'s method for hydrodynamic and sediment transport modelling. However, only the effects of ripples and mega ripples were taken into account in the models of Teske (2013). The field evidence in similar environments (water depth, bed sediments, tidal currents and waves) of the Marsdiep inlet suggests that, for the inlet tidal channels, the dune roughness is much larger than that of the mega-ripples and ripples (Buijsman and Ridderinkhof, 2008).

Another approach is involving sediment grain-size sorting processes. If multiple bed sediment fractions are employed in the morphodynamic model, their different transport capacities result in changes not only in the morphological evolution but also the bed sediment composition (Geleynse et al., 2011; Dissanayake and Wurpts, 2013). The strong currents within deep inlet channels cause bed coarsening which prevents channel incision (Dastgheib, 2012; Wang et al., 2014a, 2014b). Furthermore, bed sediment grain size variations also affect the bedform development (Ernstsen et al., 2005; van Rijn, 2007a), and thus, the sorting processes interact with the bedform development, which are possible to play a substantial role in channel morphodynamics.

The present study couples the bedform roughness and sediment grain-size sorting in the decadal morphodynamic modelling of the Amelander Inlet (Fig. 1), which is an inlet connecting the Dutch Wadden Sea and the south North Sea. Firstly, the contributions of different bedform types to the total bedform roughness and the usage of the van Rijn (2007a) bedform roughness predictor in tidal environments are investigated by short-term hydrodynamic modelling. Secondly, based on the tide only model as initial explorations, the effects of bedform roughness and sediment grain-size sorting were coupled in the morphodynamics in a decadal time scale. The objectives of the present study are to identify contributions of these two effects on the inlet channel morphodynamics, and find out the key factors controlling the channel incision.

2. Study area

The Amelander Inlet is between the barrier islands of Terschelling and Ameland of the Dutch Wadden Sea (Fig. 1). It is the inlet with the least human interferences within the Dutch Wadden Sea and therefore shows the most natural behaviors. It is a typical meso-tidal inlet system with an ebb tidal delta, a main inlet channel, and a back-barrier tidal basin (Hayes, 1979). The basin area is about 270 km^2 and the tidal prism is ca. 480 million m^3 (Sha, 1989). The tidal forcing is characterized by a semidiurnal tide with a mean tidal range of 2.15 m, and the dominant wave direction is from northwest and the average significant wave height is about 1.0 m at the sea side of the inlet (Cheung et al., 2007). Within the inlet system, most of the bed materials are fine sands with mean grain size of about 250 μm, and in the inlet channel area, the mean grain size increases to 300–400 μm. A key character of the main tidal channel of the Amelander Inlet is that, although the channel migrated periodically during the last 10^2 years, the maximum depth mostly keeps smaller than 25 m (Elias et al., 2012b; Teske, 2013).

3. Methods

3.1. Model description

3.1.1. Hydrodynamic modelling

In this study, a two-dimensional, depth-averaged (2DH) process-based morphodynamic model (Delft3D) was utilized (Lesser et al., 2004). The two-dimensional depth-averaged continuity equation and nonlinear, shallow-water momentum equations for incompressible free surface flow were solved numerically. In Delft3D-FLOW module, the computational part is protected against "dividing by zero" by assuming that the total water depth is at least 10% of the drying and flooding threshold (Dryflc). The threshold depth (SedThr) is defined as the minimum water depth for computing sediment transport.

3.1.2. Sediment transport and morphological evolution

Non-cohesive sediment transport was calculated by van Rijn (2007a, 2007b)'s approach (see Delft3D-Flow manual for a full reference), and the standard advection–diffusion equation was employed for suspended sediment transport. Both suspended load and bed-load were involved in the Exner equation for sediment mass conservation