Coastal Engineering 132 (2018) 33–49

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Modelling of bed sediment composition changes at the lower shoreface of the Sand Motor

B.J.A. Huisman[a,b,*], B.G. Ruessink[c], M.A. de Schipper[a,d], A.P. Luijendijk[a,b], M.J.F. Stive[a]

[a] Delft University of Technology, Faculty of Civil Engineering and Geosciences, Department of Hydraulic Engineering, P.O. Box 5048, 2600GA, Delft, The Netherlands
[b] Deltares, Unit Hydraulic Engineering, Department of Harbour, Coastal and Offshore Engineering, P.O. Box 177, 2600MH, Delft, The Netherlands
[c] Utrecht University, Faculty of Geosciences, Department of Physical Geography, P.O. Box 80115, 3508TC, Utrecht, The Netherlands
[d] Shore Monitoring and Research, P.O. Box 84070, 2508AB, The Hague, The Netherlands

ARTICLE INFO

Keywords:
Nourishment
Bed sediment
Sorting
Grain size
Numerical modelling

ABSTRACT

Large perturbations in the coastline, such as the 'Sand Motor' nourishment (~21 million m^3) at the Holland coast, can initiate considerable spatial and temporal changes in the median grain size (D_{50}) of the sea bed on the lower shoreface. The relevance of hydrodynamic conditions for the development of the heterogeneity in D_{50} at large-scale nourishments was assessed with a numerical model (Delft3D), which required a validation against 2.5 years of D_{50} measurements. A good representation of the observed spatial pattern of D_{50} was obtained independent of a 2DH or 3D approach and initial condition for the D_{50} of the bed. Five sediment size fractions and a multi-layer administration of the bed composition were used. The extent and magnitude of the coarsening of the bed is related to the velocity of the horizontal tide, while a far less pronounced coarsening takes place during energetic conditions (i.e. $H_{m0} \geq 3$ m). Differential suspension behaviour between the size fractions, which are all mobilized at the bed, causes a preferential transport of fine sediment (in alongshore direction) away from the Sand Motor at the lower shoreface (i.e. seaward of MSL -6 m). Storm conditions may induce a partial removal of the coarse top-layer due to mobilization of all of the size fractions and mixing with the relatively fine substrate material. Simulations also show that transport of the fine sand fraction extents to much deeper water than for the medium and coarse sand fractions. Models with multiple sediment fractions are therefore required for the assessment of environmental impacts of large-scale coastal structures or land reclamation's and sediment transport on the lower shoreface.

1. Introduction

Spatial heterogeneity of bed sediment composition is observed at many coasts around the world (Holland and Elmore, 2008), but seldom accounted for in morphological or environmental impact studies of coastal interventions (e.g. modelling of sand nourishments; Capobianco et al., 2002). Knowledge of the potential spatial variability of the bed sediment (i.e. grain size and grading) is however considered essential for the understanding of the ecological impact of large-scale coastal interventions. Firstly, bed composition changes affect the ecological habitats for benthic species and fish (e.g. McLachlan, 1996; Knaapen et al., 2003). Small changes in the top-layer grain size can, for example, significantly affect the burrowing ability of juvenile plaice (Gibson and Robb, 1992). Secondly, long-term morphological changes can be affected by bed coarsening when preferential transport of finer sand fractions takes place at large-scale sand nourishments (Van Rijn, 2007b), which is especially relevant for the region outside the surfzone (Huisman et al., 2016).

Spatial heterogeneity of the bed composition of natural coasts is characterized by a fining of sediment grain size in the offshore direction with coarsest sediment being found in the swash zone (Inman, 1953; Sonu, 1972; Liu and Zarillo, 1987; Pruszak, 1993; Horn, 1993; Stauble and Cialone, 1996; Kana et al., 2011). In the presence of sub-tidal bars the spatial pattern of the bed sediment composition can vary between different studies. Generally, coarser sediment is observed in the bar troughs and finer sediment on bar crests (Moutzouris et al., 1991; Katoh and Yanagishima, 1995), but Van Straaten (1965) and Guillén and Hoekstra (1997) observed coarser material on the bar crests for the Dutch coast. Considerable spatial heterogeneity of the sediment grain size is also observed at rip-bar systems with coarser sediment in the

---

* Corresponding author. Delft University of Technology, Faculty of Civil Engineering and Geosciences, Department of Hydraulic Engineering, P.O. Box 5048, 2600GA, Delft, The Netherlands.

E-mail address: bas.huisman@deltares.nl (B.J.A. Huisman).

https://doi.org/10.1016/j.coastaleng.2017.11.007
Received 7 February 2017; Received in revised form 16 September 2017; Accepted 11 November 2017

rip-channels (MacMahan et al., 2005; Gallagher et al., 2011; Dong et al., 2015). Coarsening of the bed (change in median grain diameter D_{50} of about $+150$ μm) as a result of alongshore transport processes was observed at a large-scale sand nourishment at the Dutch coast ('The Sand Motor'; Huisman et al., 2016). This study also showed that the alongshore changes in D_{50} are related to spatial variability in the hydrodynamic forcing conditions.

The impact of storm conditions at natural coasts typically consists of a coarsening of the sediment grain size. Most prominent coarsening of the median grain diameter (D_{50} up to 100 μm coarser), during a storm event with offshore significant wave height of $H_{m0} = 4$ m, was observed in the swash zone (Stauble and Cialone, 1996). This coarsening gradually decreases in the offshore direction. Terwindt (1962) observed a quite uniform coarsening of ~30 μm from 2 to 6 m water depth at the coast of Katwijk (The Netherlands) after a moderate summer storm ($H_{m0} \approx 2$ m). Numerical modelling of cross-shore transport sorting during storms also shows coarsening of the nearshore zone and subsequent fining of the offshore sediment at the toe of the deposition profile (Reniers et al., 2013; Sirks, 2013; Broekema et al., 2016). Seasonal variability of the cross-shore distribution of the grain size, as observed by Medina et al. (1994), comprised nearshore bed composition coarsening in winter ($H_{m0,winter} \approx 4$ m) and restoration to a finer bed composition in summer ($H_{m0,summer} \approx 1$ m). The largest annual variability in the measured D_{50} was observed in the swash zone (up to 200 μm) at mean sea level (MSL) which gradually decreased to a variability of ~20 μm at MSL -8 m. Seasonal variability of the D_{50} was, however, found to be almost negligible for a nourishment at the Dutch barrier island of Terschelling (Guillén and Hoekstra, 1996). Guillén and Hoekstra (1996) observed an 'equilibrium distribution' of the size fractions, which means that the cross-shore bed composition of each size fraction will be restored over time by the hydrodynamic processes to the natural equilibrium situation. An influence of the width of the littoral zone (which depends on the wave conditions) on the location of transitions in the cross-shore grading of the sediment was suggested by Guillén and Hoekstra (1997).

Spatial variability of the grain size (on cross-shore profiles or alongshore) is often the result of differences in the behaviour of sediment grain size fractions for the same hydrodynamic forcing conditions (e.g. for bimodal sand in Richmond and Sallenger, 1984). Sorting processes at the scale of the sediment grain can induce sorting mechanisms of which settling, entrainment and transport sorting are considered most relevant (Slingerland and Smith, 1986). Sorting due to settling, for example, plays a role in sedimentary environments where fine grains are deposited over a much larger distance than the coarse grains (Baba and Komar, 1981). Entrainment sorting is the result of differences in the suspension of sediment grain particles into the water column, which is affected by the size and weight of the particle (Komar, 1987) as well as the density of the grains (Steidtmann, 1982). Investigations on the critical limit for suspension of the sediment into the water column were made by Bagnold (1966) (and other researchers) who indicates that the 'initiation of suspension' is related to the shear velocity at the bed (u^*) and the fall velocity (w_s) of the sediment particle (see also Van Rijn, 1993). The finer sediment, that is suspended higher up in the water column (Rouse, 1950), is typically advected over a longer distance by the currents. The availability of the size fractions in the bed is also of relevance for the transport sorting as it determines the (reference) concentrations. These sorting processes may act together and induce a 'preferential transport' of (fine) sediment size fractions at locations where substantial gradients in the hydrodynamic forcing conditions are present. Hiding and exposure mechanisms (i.e. hiding of fine grains and exposure of coarse grains; Egiazaroff, 1965; Ashida and Michiue, 1973), on the other hand, may reduce the preferential transport for conditions which are at (or very close to) the critical shear stress for mobility of the sediment mixture. The individual sediment size fractions in the sand mixture (in unilateral flows) are then expected to behave similarly as they are mobilized at the same critical shear stress (Wilcock, 1993). Conditions in the marine environment are, however, typically above the mobility threshold and closer to the critical limit for initiation of suspension as a result of wave stirring (e.g. Holland coast; Huisman et al., 2016).

The modelling of changes in bed sediment composition can be performed either with data-driven models or numerical models. Data driven models use observed knowledge on the sediment distribution at the considered coast to derive the transport processes and/or predict future changes in bed composition. For example, Guillén and Hoekstra (1996) introduced the concept of an equilibrium cross-shore distribution of sediment size fractions for a beach at Terschelling (The Netherlands). Any change to the cross-shore distribution of a size fraction will result in a redistribution of sediment until the equilibrium cross-shore distribution is restored (Guillén and Hoekstra, 1996). McLaren and Bowles (1985) proposed a method to track the transport direction of (graded) sediment on the basis of spatial differences in the sediment grading. The derived properties of the grading (i.e. mean size, standard deviation and skewness) change in a logical way along the transport path. Other studies, however, suggest that only a better sorting provides a consistent proxy for the pathways of the sediment (Gao and Collins, 1992; Masselink, 1992).

Numerical models (e.g. Delft3D; Lesser et al., 2004) are more suitable than data-driven models for investigating situations where a local equilibrium is not available. Sediment transport rates and bed composition changes are computed per sediment size fraction on the basis of the forcing conditions in the numerical models (Van Rijn, 2007b). Typically an administration of bed composition changes is applied for a discrete number of layers of the bed and an active layer concept (Ashida and Michiue, 1973; Ribberink, 1987). The capability of numerical modelling of sediment transport with multiple size fractions was shown, for example, by Van Rijn (1997) for cross-shore sorting during storms. Furthermore, numerical modelling of sediment sorting was compared to field and laboratory experiments for a river bifurcation in the Netherlands (Sloff and Mosselman, 2012) and detailed sorting at river dunes (Blom and Parker, 2004). Even the generation of river deltas was modelled by Geleynse et al. (2011) who found that models could reproduce the typical plan-form shapes of river deltas which depends both on the supply of sediment and local hydrodynamics. Applications of numerical modelling of the redistribution of non-uniform sediment are, however, missing for sand nourishments at natural coast where a large influence of alongshore redistribution of sediment can be expected.

The objective of this work is to assess the relevance of hydrodynamic conditions for the development of heterogeneity in D_{50} just outside the surfzone of a large-scale nourishment. This required a validation of the numerical model Delft3D against observed spatial and temporal changes in D_{50} over a period of 2.5 years after construction of the large-scale 'Sand Motor' nourishment (Stive et al., 2013) to allow the investigation of underlying processes. Simplified hydrodynamic conditions were then used in the model to exemplify the influence of individual conditions.

2. Study area

The study area is located between Monster and Kijkduin on the southern part of the Holland coast (the Netherlands). A large-scale sand nourishment referred to as the 'Sand Motor' was constructed here from April to June 2011 (~21.5 million m^3; Stive et al., 2013). The planform design of the Sand Motor comprised of a hook-shape with a dune lake and open lagoon on the landward side (Fig. 1) with an alongshore extent of about 2.5 km and a cross-shore width of about 1 km at the waterline. The foot of the nourishment attaches to the natural bed at a depth of about 10 m.

Bathymetric changes after construction of the Sand Motor were monitored at 1–3 month intervals. In the first period after completion a large morphological response of the Sand Motor was observed (de Schipper et al., 2016), as about 1.8 million m^3 of sand was spread alongshore. The initial blunt shape was reformed in a smooth planform shape (see Fig. 2). The nearshore bathymetry at the Sand Motor is characterized either by sections with a longshore uniform bar-trough