Marine Geology 381 (2016) 209–226

Contents lists available at ScienceDirect

Marine Geology

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

Sediment sorting at the Sand Motor at storm and annual time scales

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

[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] Shore Monitoring and Research, P.O. Box 84070,2508AB The Hague, The Netherlands
[d] Utrecht University, Faculty of Geosciences, Department of Physical Geography, P.O. Box 80115, Utrecht 3508TC, The Netherlands

ARTICLE INFO

Article history:
Received 25 April 2016
Received in revised form 29 July 2016
Accepted 6 September 2016
Available online 12 September 2016

Keywords:
Nourishment
Bed sediment
Alongshore heterogeneity
Sorting
Morphology

ABSTRACT

Bed sediment composition, with a focus on the median grain size D_{50}, was investigated at a large-scale nourishment (The 'Sand Motor') at the Dutch coast (~21.5 million m^3 sand). Considerable alongshore heterogeneity of the bed composition (D_{50}) was observed as the Sand Motor evolved over time with (1) coarsening of the exposed part of the Sand Motor (+90 to +150 μm) and (2) a depositional area with relatively fine material (50 μm finer) just North and South of the Sand Motor. The alongshore heterogeneity of the measured D_{50} values was most evident outside the surfzone (i.e. seaward of MSL −4 m). Coarsening of the bed after construction of the Sand Motor was attributed to hydrodynamic sorting processes, because the alongshore heterogeneity of the D_{50} showed a similar spatial pattern as the mean bed shear stresses. The observed alongshore heterogeneity of the D_{50} and correlation of D_{50} with modelled mean bed shear stresses suggest that preferential erosion of the finer sand fractions has taken place. The selective transport of finer sand fractions results in a coarser top layer of the bed at the Sand Motor. The preferential transport is most dominant during mild and moderate conditions when hydrodynamic forcing conditions are close to the critical bed shear stresses for transport. The measurements also show the impact of a storm, which consists of a ~40 μm finer D_{50} of the offshore bed composition in front of the Sand Motor (i.e. where a considerably coarser bed was in place). Additionally, storms may generate a (temporary) zone with fine bed material at the toe of the deposition profile. This means that the coarsening of the bed is reduced by storms as a result of the mobilization of both coarse and fine sediment and mixing of the bed with the relatively finer substrate.

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 (i.e. centimeters) grain size can, for example, significantly affect the burrowing ability of juvenile plaice (Gibson and Robb, 1992). Secondly, long-term morphological changes may be affected by bed coarsening when finer sand fractions are predominantly eroded (Van Rijn, 2007). Furthermore, the development of the morphology of rip-bar systems was found to be inter-related with the bed sediment (Gallagher et al., 2011; Dong et al., 2015).

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; Horn, 1993; Pruszak, 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) observed coarser material on the bar crests for the Dutch coast. Considerable spatial heterogeneity of the sediment grain size was also observed at rip-bar systems with coarser surface sediment in the rip-channel and finer sediment at the head of the transverse bar (MacMahan et al., 2005; Gallagher et al., 2011). Gallagher et al. (2011) applied a mobile digital imaging system which

---

* Corresponding author.
E-mail addresses: bas.huisman@deltares.nl (B. Huisman), M.A.deSchipper@tudelft.nl (M. Schipper), B.G.Ruessink@uu.nl (B. Ruessink).

http://dx.doi.org/10.1016/j.margeo.2016.09.005

derived D_{50} from 2D autocorrelation of macro images of the surface sediment (Rubin, 2004).

The impact of storm conditions at natural coasts 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 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 15 meter water depth at the coast of Katwijk (The Netherlands) after a moderate summer storm (H_{m0} ~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., in press). Seasonal variability of the cross-shore distribution of the grain size was observed by Medina et al. (1994), who shows that nearshore bed composition is coarsening in winter ($H_{m0,winter}$ =~ 4 m) and restoring to a finer bed composition in summer ($H_{m0,summer}$ =~ 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 decreases to a variability of ~20 μm at MSL –8m. 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 spatial variability in D_{50} of the sediment was suggested by Guillén and Hoekstra (1997).

The impact of the wave-driven longshore current on the alongshore heterogeneity of the bed composition was investigated by McLaren and Bowles (1985) with a focus on the changes of the sediment grain size distribution (size, standard deviation and skewness) along the transport path. A coastal section down-drift from a cliff was studied by McLaren and Bowles (1985) as well as some riverine cases. McLaren and Bowles (1985) observed two typical spatial patterns of changes of the grain size distribution in the direction of the transport, which were either finer, better sorted and more negatively skewed (abbreviated as FB−) or coarser, better sorted and more positively skewed (CB+). Other studies do, however, suggest that only a better sorting provides a consistent proxy for the pathways of the sediment (Gao and Collins, 1992; Masselink, 1992). The alongshore gradients in the D_{50} were generally quite small at the Rhone Delta (~10 μm per kilometer; Masselink, 1992) and therefore seldom larger than the natural variability of the D_{50} (Guillén and Hoekstra, 1997). In general it can be stated that the literature on the impact of the littoral drift on the spatial variability of the bed composition is scarce, which holds especially for cases with large-scale interventions where sand is expected to diffuse alongshore.

The geological history (e.g. presence of former river bed deposits) also influences the spatial heterogeneity of the local bed composition but at a very large time-scale (millenia or longer; Van Straaten, 1965; Eisma, 1968). The geological situation is therefore often seen as an initial condition of the bed which determines the mean bed composition in the region (Medina et al., 1994; Guillén and Hoekstra, 1996). In general it can be stated that the relevance of the geological history is largest in areas where hydrodynamic forcing conditions are weaker (e.g. at deeper water) and subsequently the time scale of sediment redistribution is long (i.e. months to years).

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 (Richmond and Sallenger, 1984) which takes place at the spatial scale of sediment grains. A differentiation can be made in sorting due to transport, suspension and entrainment of the grains (Slingerland and Smith, 1986). The transport sorting process is induced by the difference in magnitude of the transport for fine and coarse size fractions (Steidtmann, 1982). A larger proportion of the finer size fraction is transported away from an erosive coastal section than of the coarser size fractions. Differences in sediment fall velocity may for specific situations induce suspension sorting (Baba and Komar, 1981). The spatial scale of the area over which sediment is deposited is larger for smaller grains. Additionally the difference in the weight and size of the particle may induce preferential entrainment of the finer sand grains for regimes that are close to the critical bed shear stress of the sand (Komar, 1987). These 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. It is envisaged that the 'Sand Motor' nourishment (Stive et al., 2013) provides an ideal case study site to investigate these processes given the large gradients in wave energy and longshore transport.

The objective of this work is to investigate the spatial heterogeneity of the surface bed composition, with a focus on the median grain size (D_{50}), at the large-scale 'Sand Motor' nourishment (Stive et al., 2013). Sediment sampling surveys were carried out at the Sand Motor shoreface and related to modelled hydrodynamic forcing conditions (i.e. mean and maximum bed shear stresses). Both (half-)yearly and bi-weekly measurements were carried out to assess the bed composition changes at annual and storm time scales.

2. Study area

The 'Sand Motor' nourishment was constructed on the southern part of the Holland coast (the Netherlands) between April and August 2011 with the aim of providing a 20-year buffer against coastal erosion (Stive et al., 2013). A total of 21.5 million m^3 of sediment was dredged for the creation of two shoreface nourishments and a large peninsula of 17 million m^3 (de Schipper et al., 2016). The planform design of the Sand Motor comprised of a hook-shape with a dune lake and open lagoon on the northern side (Fig. 1). The alongshore extent of the Sand Motor was initially about 2.5 km. The emerged part of the Sand Motor was about 1 km wide at the Sand Motor peninsula (i.e. measured at MSL with respect to the original coastline). The initial submerged cross-shore profile slope at the center of the Sand

Fig. 1. Aerial photograph of the Sand Motor after completion (September 2011). Note the clouds of fine-grained material moving to the North. Picture courtesy of Rijkswaterstaat/Joop van Houdt.