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Observations and modelling of nearshore sediment sorting processes along a barred beach profile

Y.B. Broekema [a,b], A. Giardino [b], J.J. van der Werf [b], A.A. van Rooijen [b], M.I. Vousdoukas [c,d,*], B.C. van Prooijen [a]

[a] Delft University of Technology, Stevinweg 1, 2628, CN, Delft, The Netherlands
[b] Deltares, Marine and Coastal Systems, P.O. Box 177, 2600, MH, Delft, The Netherlands
[c] European Commission, Joint European Research Centre (JRC), Via Enrico Fermi 2749, I-21027, Ispra, Italy
[d] Department of Marine Sciences, University of the Aegean, University hill, 41100, Mitilene, Lesbos, Greece

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ABSTRACT

The understanding of cross-shore sediment sorting is of primary importance for the design of sand nourishments and for assessing the suitability of the seabed to different ecological species. In this paper, sediment sorting processes were investigated by using a combination of physical and detailed numerical modelling. Data from large-scale wave flume experiments were used to validate a 2DV cross-shore Delft3D model. The model solves coupled short-wave averaged equations for flow, sediment transport, bed composition and bed level change. The infra-gravity wave motions were explicitly resolved. In order to investigate sorting processes, eight sediment fractions were used as well as a layered bed stratigraphy. The effects of different wave conditions (high energetic and more moderate energetic waves) on the morphodynamic profile development and sorting processes were investigated. The Delft3D model reproduced the profile development and bar position very accurately. Additionally, model predictions of sediment sorting across the profile fitted very well with the available observations. The numerical model simulations showed the importance of including short-wave grouping and infragravity wave effects in order to reproduce the cross-shore profile development, especially the breaker bar dynamics and sediment sorting processes. Infragravity waves contribute to larger sediment entrainment and more offshore bar development. Besides leading to a better prediction of the bed profile, infragravity waves also lead to a better prediction of the bed composition. Model results are in agreement with experimental data, showing its capabilities in functioning as a tool to predict sorting processes.

1. Introduction

The sediment on natural beaches is not uniform, but shows a large spatial grain size variability. Cross-shore sediment sorting occurs due to the dependency of sediment transport on the local hydrodynamic conditions and the grain size of the available sediment. The heterogeneity in grain size may play an important role in the morphological development of the nearshore region of sandy beaches. Therefore, the understanding of the cross-shore sediment sorting is of primary importance, for example, for the design and construction of sand nourishments with a different grain size distribution with respect to the native beach.

Despite the known non-uniformity of natural beaches, coastal engineering models like Delft3D often assume for simplicity a uniform grain size for the prediction of beach and nearshore morphodynamics (e.g. Ruessink et al., 2007; Van Rijn et al., 2011). We hypothesize that taking into account sediment variability and sorting processes will impact the modelled morphodynamics.

Sorting of sediment is dependent on a combination of both sediment characteristics (size, shape and density) and hydrodynamic conditions. Slingerland and Smith (1986) distinguished two different hydraulic sorting mechanisms. First, suspension sorting involves separation of heavy from light materials according to their settling velocities and takes place during deposition. Second, entrainment sorting takes place during erosion and involves separation of grains according to their relative entrainment thresholds, usually expressed in terms of a critical bed shear stress (Komar and Wang, 1984).

Most of the existing studies on sediment sorting are based on field data. In general, an inverse depth dependency is found to the cross-shore grain size distribution, with several researchers mentioning a fining trend offshore. Van Rijn (1998) showed through a modelling study that fine sediments are transported seaward during periods of high wave energy. Stauble (1992) presented results from a long-term morphological study at the Field Research Facility beach at Duck, North Carolina. Although small variations occurred, a persistent pattern

* Corresponding author at: European Commission, Joint European Research Centre (JRC), Via Enrico Fermi 2749, I-21027, Ispra, Italy.
E-mail addresses: Y.B.Broekema@tudelft.nl (Y.B. Broekema), michalis.vousdoukas@jrc.ec.europa.eu (M.I. Vousdoukas).

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was found over time with sediment fining offshore up to the depth of closure. In addition to the fining trend, it was also mentioned by Van Rijn (1998) that coarser sediments are found around the bar area. Antia (1993) observed this as well at the shoreface of Spiekeroog (one of the southern North Sea barrier islands along the Dutch and German coast), where coarser sediments tend to occur in the bar troughs. In this multiple bar system, finer sediments where found on top of the bar.

A disadvantage of field data is that opposed to laboratory data, field conditions cannot be controlled and the measurements are generally less accurate (Van Rijn et al., 2013). In this study, cross-shore sorting processes along a profile have been investigated using a combination of data from physical experiments, where sediment samples were collected at regular time intervals during profile development, and detailed numerical modelling.

Besides the fact that coastal engineering models assume a uniform grain size, they often use phase-averaged wave modelling approach to limit the computational time (e.g. Wenneker et al., 2011). This means that typically in engineering models intra-wave properties such as skewness and asymmetry, stokes drift and bound infragravity (IG) waves are not resolved but parameterized (Ruessink et al., 2007; Van Rijn et al., 2011; Walstra et al., 2012). This could explain why engineering models often have difficulties predicting nearshore morphodynamics (Van Rijn et al., 2013). In this study, besides sorting we will also investigate the effect of taking into account IG waves on the computed morphodynamics.

The motivation of taking IG wave effects into account is to achieve an improved prediction of the different cross-shore transport components. A correct balance of all the cross-shore transport components is crucial to determine migration of breaker bars (Van Duin et al., 2004). Besides, several researchers have shown that long waves can have a strong impact on nearshore morphodynamics (e.g. Reniers et al., 2004).

For instance, Roelvink and Stive (1989) performed a quantitative comparison of the magnitude of the contribution of several components to the total cross-shore sediment transport along the Holland Coast. One of their findings was that IG waves give an offshore directed contribution to the sediment transport. They explained this by showing that the offshore directed velocities under the trough of the IG waves are coupled with the highest short waves within a wave group and thus resulting in the highest sediment concentrations. This was also found by Deigaard et al. (1999), who showed that IG waves can enhance offshore directed transports through mathematical modelling. Wave flume experiments performed by Baldock et al. (2010) showed that the presence of wave groups and the accompanying bound IG waves generally reduce onshore transport during accretive conditions and increase offshore directed transport under erosive conditions.

In this study, the state-of-the-art engineering numerical model Delft3D (Lesser et al., 2004) will be validated using data from laboratory experiment and used to study the effect of IG waves and sorting processes on cross-shore morphodynamics. Extra attention will be paid to breaker bar dynamics as the morphological development of the profile is strickly linked to sorting processes taking place across the profile.

This paper is outlined as follows: in Section 2 the Laboratory experiments are described while the model set-up is described in Section 3. The results are described in Section 4 and discussed in Section 5. Finally, Section 6 summarizes the main conclusion from the study.

2. Laboratory observations

Physical experiments were performed in the large scale wave flume of Hannover (GWK) as part of the WISE- (Water Interface Sediment Experiment) project. The project aimed in assessing hydrodynamics, waves and sediment dynamics at different experimental facilities (by using scaling) and with the use of innovative instruments. Due to different wave paddles and associated software at the different flumes, it was decided to avoid second order generation and the use of an active absorption system. The data gathered during the experiments used for this study contain spatial and temporal information on hydrodynamics, bed level changes and grain size distribution.

2.1. Facility and instrumentation

The dimensions of the wave flume are 300 m (length) × 5 m (width) × 7 m (height). The initial bathymetry was a plain sloping, sandy profile of 1:15 slope (Fig. 1), consisting of moderately sorted, nearly symmetrical medium sand with $d_{10} = 137$ μm, $d_{50} = 300$ μm and $d_{90} = 610$ μm.

In total 17 wire-type wave gauges were deployed to measure water levels at 120 Hz at different locations in the shoaling and surf zone (Fig. 1). In the swash zone, 8 MASSA M300/95 ultrasonic sensors were installed with 2 m spacing along the cross-shore profile and 1.7 m above the mean water level to provide point measurements of the water elevation at 120 Hz. From the ultrasonic sensors IG wave height in the swash zone was determined. The sensors were installed from x = 260 m to x = 274 m. To measure bed level changes, a mechanical profiler attached to a measuring carriage was used. The profiler was computer-controlled and the accuracy of the system was approximately 10 mm. Velocities were not measured.

To determine sediment composition sediment samples were taken at several locations along the cross-shore profile. The grain size distribution of the sample was determined by sieving the sand, using 8 sieves (0.063, 0.125, 0.25, 0.5, 1, 2, 4 and 8 mm).

2.2. Experimental conditions

The hydrodynamic conditions to which the profile was subjected during the different tests are summarized in Table 1. The initial plain sloping bed was subjected to erosive waves (storm-like conditions). The resulting (barred) profile was subjected to a milder wave climate. The first case involves breaker bar formation due to high energetic erosive waves, and accompanying sorting phenomena. Under the milder waves from Case 2 erosion and sediment sorting continued, but with a slower rate.

The classification of the waves (e.g. high energetic or moderate energetic) is based on the Dean number (Ω), following Wright and Short (1984):

$$\Omega = \frac{H_s}{T_p W_s} \tag{1}$$

where H_s is the significant wave height measured near the wave board [m], T_p the peak period [s] and w_s the sediment settling velocity [m/s]. The sediment settling velocity is determined according to Van Rijn et al. (2004):

$$W_s = \frac{10v}{D_{50}}\left[\left(1+\frac{0.01(s\text{-}1)g\,(0.8D_{50})^3}{v}\right)^{0.5}\text{-}1\right] \tag{2}$$

where $s = 2.65$ is the relative density, D_{50} is the median grain diameter [m] and ν is the kinematic viscosity [10^{-6} m^2/s]. The Dean number gives an indication on whether the response of the profile to the wave conditions will be slow (low energy, reflective) or fast (high energy, dissipative).

2.3. Methodology

Waves were generated by a wave generator. Each test case consists of several wave time series of approximately 40 min. All wave time series were generated using 1st order approximation (hence no IG waves were generated at the boundary) using a JONSWAP spectrum with spectral shape factor (γ_{JONS}) equal to 3.3. After each individual time