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EFFECTS OF DENSITY ON CROSS-SHORE SEDIMENT TRANSPORT

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Abstract: After the discovery of high concentrations of heavy minerals on the beach of the Dutch barrier-island Ameland, the radiometric fingerprinting technique was developed to assess offshore heavy-mineral concentrations. These measurements revealed cross-shore variations in the heavy-mineral concentration. To determine which mechanisms generate these variations in sediment density and what the effects of these placers are on sediment transport and profile deformation, laboratory experiments are conducted. These experiments comprise measurements of hydrodynamics, profile deformation, suspended sediment concentrations and sediment composition under storm conditions on a 1:40 sloping bed with varying sediment composition.

INTRODUCTION

Sorting of sediment by wind, waves or currents leads to concentrations of sediments with similar properties like grain size, density or shape (placers). Such placers are found in river beds, on the beach face and offshore and have been subject of many studies (see eg. Frihy *et al* (1995), Boon and Berquist (1989), Komar and Wang (1984)).

Like for many studies of nature, also for these studies sampling is a crucial and tedious procedure. Recently, techniques are being developed that allow high resolution *in situ* characterization of sediments (de Meijer 1998, Venema *et al*, 1999a, 1999b). With these techniques, large areas (>100km^2) can be surveyed in a short time and at relatively low costs. Repetitive measurements yield information on variations in sediment composition and hence on sediment transport (Venema *et al* 199a). The technique is based on the

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characterization of sediment components by their natural radionuclide content (radiometric fingerprint), (see de Meijer *et al*, 1997 and de Meijer, 1998).

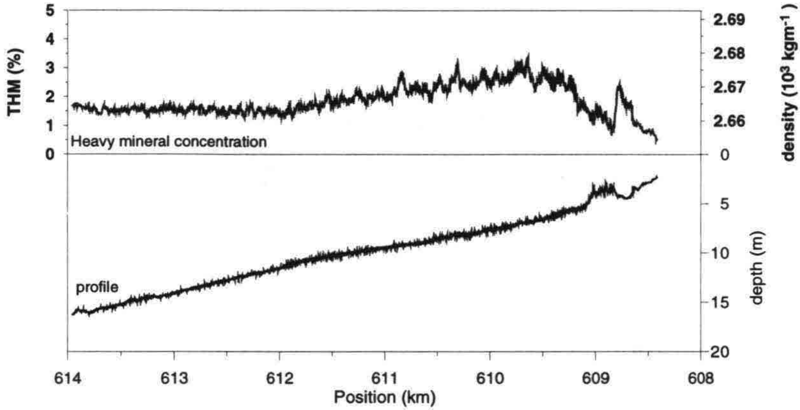

Figure 1: Average profile and total heavy-mineral concentration (THM, by weight). Measurements conducted off the coast of Ameland (The Netherlands).

After the discovery of high concentrations of heavy minerals on the beach of the Dutch barrier-island Ameland, the radiometric fingerprinting technique was developed to asses under water heavy-mineral concentrations. These measurements (Figure 1) revealed an overall long-shore consistent pattern showing cross-shore variations in the heavy-mineral concentration. These results show that heavy minerals are concentrated in the surf zone, landward of the breaker-bar and as a broad bump between the breaker-bar and the "depth of closure" (Koomans *et al* 1998). The discovery of high concentrations of heavy minerals on the beach let Stapor (1973) to conclude that the heavy minerals are pre-concentrated in a region more offshore. These concentrates are transported onshore during severe storms. The offshore high concentrations and the deposition of large quantities of heavy minerals on the beach of Ameland during a severe storm are consistent with Stapor's conclusions (de Meijer, 1998). The long-shore distribution of heavy minerals shows that sorting processes occur, but the actual transport mechanisms and the effects of these heavy-mineral concentrations on sediment transport are still poorly understood.

Within the framework of the EU project SAFE, attention is paid to questions regarding selective transport. In laboratory conditions, profile evolutions are studied. This paper deals with two of these experiments where sediments with different density but similar grain-size distributions are used. The experiments aim to yield information on the importance of natural occurring heavy-mineral placers on profile evolution and, in the longer term, to improve the efficiency of nourishment projects. In turn, the understanding of the sorting processes provides an opportunitv to use heavy mineral distributions along the profile as a monitor in coastal projects.

Small-scale flume experiments on density-grading effects were already conducted by May (1973). He studied the effects of sediment sorting by wave shoaling. With sediments with two different densities and varying grain size, several wave regimes were used to redistribute the sediments over a sloping beach. Although only limited data points are available, these experiments show that heavy minerals are sorted and that the degree of sorting depends on the location on the profile. High-resolution measurements of sediment sorting in wave tunnel experiments (Tánczos, 1996) were used to determine the heavy mineral fraction in the transported sediment. These measurements showed that light and heavy-minerals have different transport rates under asymmetric wave motion. Moreover, the total sediment transport rates decreased by a factor two compared to experiments with only light minerals, which is attributed to an armouring effect.

EXPERIMENTAL SET UP

The focus of present experiments is twofold: studying the differences in profile evolution and sediment transport when the profile consists of sediments with different densities, and the experiments aim to provide high resolution time dependent data of wave height, suspended sediment concentrations and velocities over the entire profile. The basic set up of the experiment is according to test 1 of Roelvink and Stive (1989).

Table 1: The grain size properties, settling velocities and density for Quartz and Zircon.

Sediment	D_{50} (µm)	Ws_{50} (mms^{-1})	ρ (10^3 kgm^{-3})
Quartz	129	12	2.4
Zircon	115	27	4.4

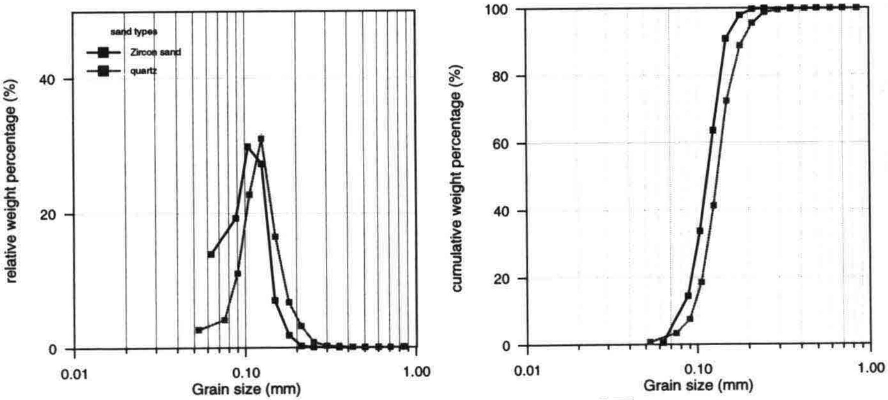

Figure 2: Grain-size distribution for Quartz and Zircon

To study the effect of density only, sands with a similar grain size distribution but with different densities are used. Therefore, hiding effects can be ignored. Table 1 and Figure 2 summarise the sediment properties of the dune sand (Quartz) and Zircon. The grain-size distribution in Figure 2 shows similar distribution for both sediments, but with a somewhat smaller grain size for Zircon. Both sediments are somewhat coarser than the sediment used in the reference experiment of Roelvink and Stive (1989) and it is expected that sediment transport rates will be smaller than for the reference experiment.

The experiments were carried out in the Scheldt flume of WL|DELFT HYDRAULICS, the Netherlands. This facility has a length of 55 m, a width of 1.0 m and a total depth of 1.2 m.

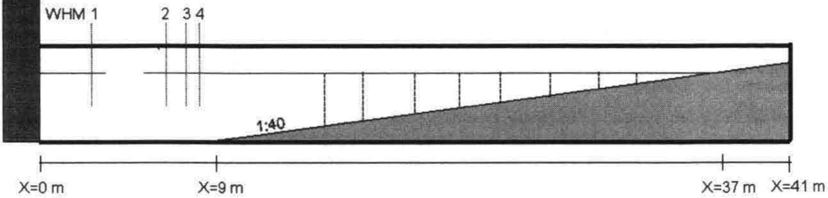

Figure 3: Schematization of the beach set-up, the positions of the wave height meters (WHM) and locations of the measurement verticals (dotted lines). The wave paddle is located on the left side of the picture.

The total measurement programme consisted of four series of which two are described in this paper: series A with a flat, 1 in 40 sloping, bed of dune sand (Figure 3). Series C started again from a 1 in 40 bed, in which the upper 10 cm of the bed consisted of a mixture of ~60% dune sand and ~40% Zircon by mass. A more elaborate description of the time dependent measurements for the A and C series can be found in Bosboom *et al*, 1999.

Table 2: Experimental program of the two different series.

Series	Initial geometry	Sediment composition (weight percentage)	Total wave duration (hrs:min)
A	Plane, 1:40	100 %Sand	28:27
C	Plane, 1:40	60% sand, 40% Zircon	14:33

Random waves were generated by a wave board equipped with an active wave absorption system (Kostense, 1984), such that at the same time second-order Stokes waves were generated and reflected waves were absorbed. The random wave fields generated were of the Jonswap type with a peak enhancement factor of approximately 3.3 representing a young sea state as expected under normal storm conditions. The maximum water depth was larger than for the reference experiment and the incident wave conditions at deep water (water depth h = 0.7 m) are scaled, resulting in $H_{m0} = 0.17$ m and $T_p = 2$ s. The wave-board control signal repeated itself every 1820 seconds.

Measuring techniques

Bottom-profile variations were measured with a profile follower (PROVO). This bed-level profiling system is mounted on a carriage on a rail that can move with a speed of 10 cm/s. The profile was measured at at least two locations in the cross direction of the flume, and in several cases, the middle part of the flume was measured as well. The profiles were recorded with a spatial resolution of 4 mm.

The *in-situ* measurements of bed composition are conducted by using the MEDUSA detector system (de Meijer, 1998). This detector determines the concentration of Zircon from the radionuclide content of the sediment bed. To guarantee a constant geometry, the set up was such that the detector was in contact with the sediment (Figure 4). The system was placed in two cylindrical tubes(one for the detector and one for the associated electronics), of which the detector tube was connected to an aluminum rod. This rod was connected to the Provo carriage such that it could be moved over the profile. Both tubes were placed on a PVC sledge to prevent sediment to pile up in front of the tubes dragged over the sediment. The concentration of Zircons in the upper layer of the sediment is calculated from the measured radionuclide activity concentrations using the Zircon fingerprint and after corrections for geometry and the attenuation of the signal by the sediment according to Debertin and Helmer, 1988.

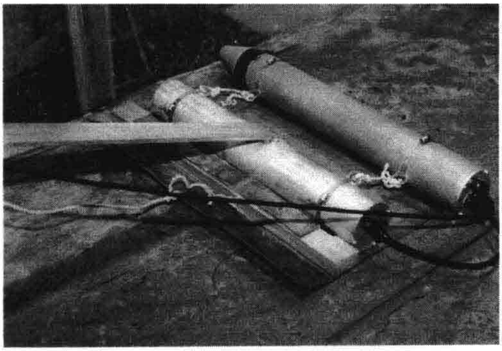

Figure 4: Set up of MEDUSA detector with the sledge, tube with detector (connected to aluminum rod) and tube with electronics

The measurements on suspended sediment concentrations were conducted with a transverse suction system (Bosman, 1987). For the A-series the suspended sediments were collected in a calibrated volume-meter and concentrations (by weight) could be calculated. The samples from the measurements in the C-series were weighed directly.

RESULTS

Profile evolution

During the experiments with the Quartz sediment bed (series A), a single barred profile developed. Figure 5 shows the initial profile of series A and the profile after 14 hours of waves. On the beach face (at a height of 0.7m), a swash bar is formed, while a breaker-bar is located at x=25 m. Between the swash bar and the breaker-bar, erosion left a trough with a steep slope at the beach face. For the experiments with the mixed sediment, similar features are observed: after 14 hours of waves a swash bar is formed at a similar position as the swash bar of the A-series. Also in these series a breaker-bar is formed, but the crest is located more seawards. The shape of the profiles on the seaward side of the breaker-bar is identical, but between breaker-bar and beach differences in the profiles of both series occur. The crest of the series-C breaker-bar is much more pronounced and is flanked on the landward side by a steeper trough. This trough flattens towards the beach and between x=33m and x=37m, the final C-series profile is comparable to the initial profile, whereas in the A-series erosion occurred at this location.

Sediment transport rates

From the profile evolution, sediment transport rates are calculated. These volumetric transport rates can only be calculated if changes in porosity are negligible and if the total amount of sediments is preserved. By adding the sand to the flume special attention was paid to pack the sand properly. Changes in porosity during the experiments are assumed to be negligible. The transport rates for both series are shown in Figure 5. A convention is adopted in which a positive sediment transport is directed to the coastline, negative transport rates point to offshore sediment transport.

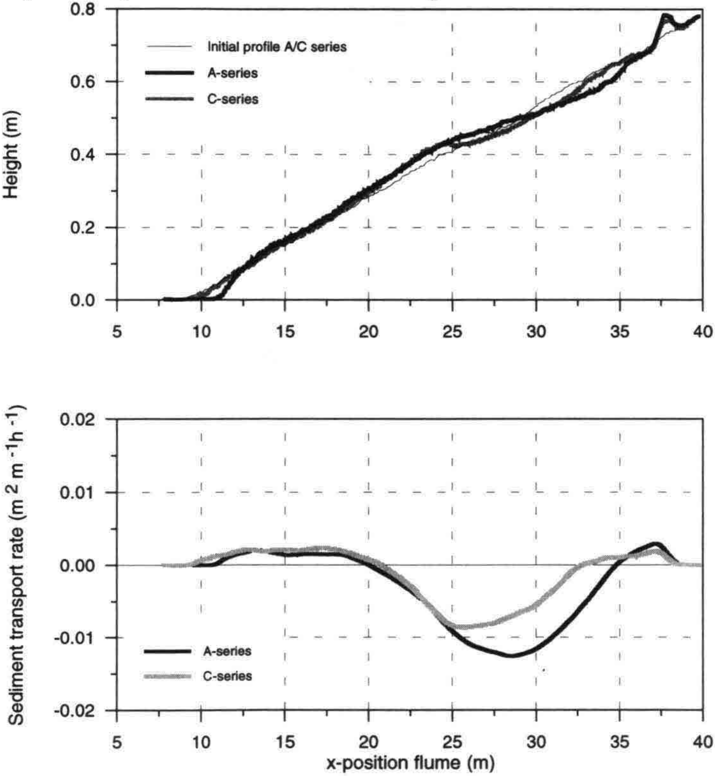

Figure 5: Profile evolution and sediment transport rates for the A and C-series after approximately 14 hours of waves.

For both experiments, the sediment transport rates reach a more or less steady state after 4 hours of waves and remains more or less constant throughout the experiments. For the A-series the overall pattern shows that sediment transport at positions x<20m is directed shoreward and between x=20m and x=35m, a seaward transport occurs. These transport rates result in the development of a breaker-bar at x=25m. The landward-directed transport rates at x>35 m generate the swash bar that is formed at the "shore"-line. The overall pattern for the C-series shows at x-positions <20m shoreward directed sediment transport, while seawards directed sediment transport occurs between x=20m and x=33m. Landward from x=33m, sediment transport is directed shorewards.

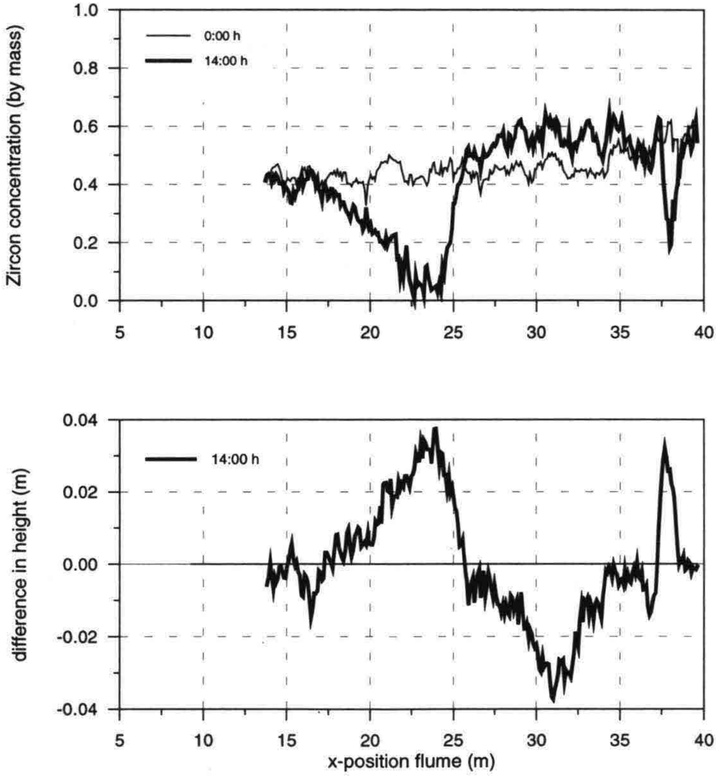

Figure 6: Zircon concentration in the upper 5 cm of the sediment bed (upper figure) and differences in bed height (lower figure) as function of position along the profile.

Heavy-mineral distribution

Since we are only interested in the sediments that actively participate in the sedimentary processes, the concentration of heavy minerals is determined for the upper 5 cm of the sediment bed. Measurements show that changes in morphology do not exceed this 5 cm and the 5cm active layer is probably and overestimation. The concentration of heavy-minerals is calculated by assuming a homogeneous mixing of sediment in the upper layer. Figure 6 shows the concentration of the Zircons in the upper layer of sediment at the start of the C-series and after 14 hours of waves. The original concentration of Zircons in the sediment was ~40% (by mass). Figure 6 shows that maximum Zircon concentrations occur between x=26 and x=37m (~60%). Note that at x=25m, the location of the breaker-bar, the zircon concentration changes an order of magnitude and decreases to ~0%. At the breaker-bar, the Zircon concentration is inversely correlated to the change in volume (lower part of Figure 6) indicating that only Quartz is deposited on the breaker-bar. In the region landward of the breaker-bar, the Zircon content shows a general increase while the difference in height varies considerably, but is in general erosional. The Zircon content decreases on the crest of the swash bar. Analysis shows that within the uncertainties, the total concentration of Zircons is preserved. This shows that the active layer of 5cm is not underestimated.

Suspended sediments

During the experiments, suspended-sediment concentrations were measured at different heights above the bed. Figure 7 shows the time averaged suspended sediment concentrations (in g/l) at eight positions along the profile for the A and C series. For x-position 33m and 30.5m, the concentrations in the mixed sediment (series C) are smaller. For the vertical at x=28m, the suspended sediment concentrations were measured at two moments: after 0:30 hrs and after 6:40 hours of waves. The suspended sediment concentrations measured after 0:30 hrs are similar to the measurements from the A-series, whereas after 6:40 hrs the suspended sediment concentrations are considerably lower. Also the vertical profile at x=23 m shows slightly decreased concentrations for the mixed sediment. At the other locations suspended sediment concentrations distributions over height for the A and C series are similar in magnitude and shape.

DISCUSSION

General observations

A comparison of the profile developments and the suspended sediment concentrations of the A and C series indicates that the breaker-bar acts as a division between two regimes. Seawards of the breaker-bar no differences between the two series are observed in the bed profiles, deduced transport rates and suspended sediment concentrations. The breaker-bar itself is wider in the A-series than in the C-series. Landwards of the breaker-bar, large differences between the A and C- series occur in the bed profile and transport rates; the concentrations of suspended sediments differ an order of magnitude and vary in shape.

Seaward of the breaker-bar crest

After the initiation of sediment transport, a clear division arose between the original sediment bed and the overlying sediment of the breaker-bar. Where the underlying sediment was dark of heavy minerals, the new deposited sediments had a distinctive lighter colour and seemed to have much lower Zircon concentrations. The boundary between both sediments was sharp. This observation and the inverse relation between bed morphology and Zircon concentration demonstrates that mainly Quartz minerals are deposited on the breaker-bar. The Quartz minerals cover the original sediment bed and the Zircons in that location are covered and not available for transport. The results from the suction system and the fact that the sediment transport rates for both series are equal, indicate that only Quartz minerals are involved in sediment transport in this region.

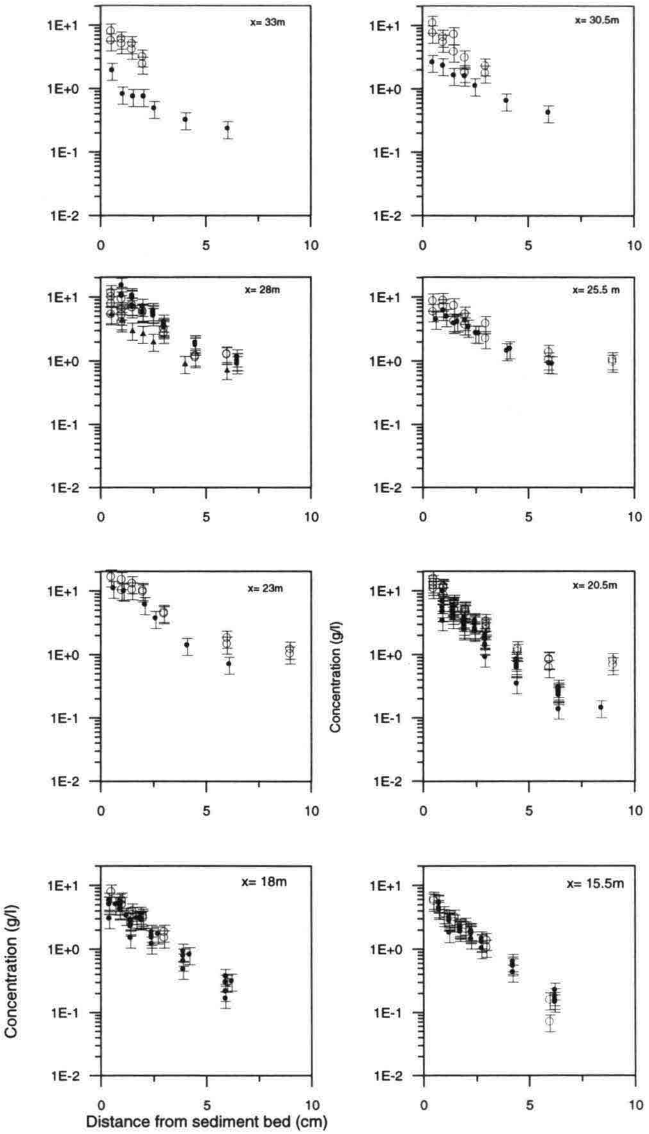

Figure 7: Suspended sediment concentrations as function of height above the sediment for different positions along the profile. Open and closed symbols refer to the A and C series respectively. For position x=28m, the closed circles indicate measurements after 0:30 hrs, the closed triangles indicate measurements after 6:30 hrs.

Landward of the breaker-bar crest

In total, the Zircon content shows an increase in this region (20% on the average), while morphology points to erosion. This suggests a selective removal of Quartz towards the breaker-bar, which in turn corroborates with the deposition of Quartz in the region of the breaker-bar. On a smaller scale however, the variations in the concentration of Zircons are not correlated to the erosion patterns. On the contrary, the concentration of Zircons is more or less constant over the profile while profile deformation points to varying erosion rates. This suggests that the sediments, which are enriched in heavy minerals, are redistributed over the region and both Zircon and Quartz participate in sediment transport. The offshore volumetric transport rates in the direction of the breaker-bar are smaller for the mixed sediment bed than for the pure Quartz, resulting in a smaller breaker-bar and less erosion near the water line.

The decreased suspended sediment concentrations for the C-series of this part of the profile are in agreement with the decreased sediment transport rates. Here, suspended sediment concentrations are reduced when both minerals are entrained. The, with time decreasing, suspended sediment concentration at x-position 28m is probably caused by an increased concentration of Zircon in the sediment in the first time intervals. In the first half-hour of the experiment, light particles are fully available and sediment transport will not be hindered by the heavy Zircons. After the Zircons have been concentrated in the sediment bed, sediment transport is reduced. Future analysis of samples from the suspended sediment will give more information on the type of sediments that are transported.

From these observations one can conclude that armouring effects are present in this part of the profile.

Comparison with natural conditions

The offshore heavy-mineral distribution near the coast of Ameland (Figure 1) increases from the beach towards the breaker-bar where it shows a drastic dip. Seawards from the breaker-bar, it increases rapidly to a maximum at a water depth of about 8m; further seawards the concentration decreases gradually. The Zircon concentration in the experiments shows a high Zircon content from the beach towards the breaker-bar where it decreases rapidly due to the accretion of almost pure Quartz. From the breaker-bar seawards it increases gradually and remains more or less constant. The Scheldt flume profile is too short to observe the behaviour at greater depths. These patterns are comparable and show that the experiments have a relation with the measurements in the field.

The decreased Zircon concentration on the breaker-bar is the result of selective sedimentation of light minerals and not by a removal or transport of Zircons. The clear separation of the two regions give the impression that, under these experimental conditions, the systems are not connected and Zircons from the lower part of the profile are not transported over the breaker-bar towards the surf zone.

CONCLUSIONS

To determine the effects of sediment density on transport along a coastal profile, storm conditions are simulated in a laboratory set up. The results of this study show that the breaker-bar acts as a division between two regimes: a region seaward from the breaker-bar crest where Quartz minerals accumulate and a region region landwards of the breaker-bar, where both Quartz and Zircon are transported but with an overall selective removal of Quartz sediments. The breaker-bar is merely composed of Quartz.

In the region landwards of the breaker-bar, sediment transport decreases when heavy-minerals are added to the profile resulting in a decreased erosion at the beach face. In the region seawards of the breaker-bar mainly Quartz minerals are transported and effects on sediment transport rates are not observed. Moreover, the patterns of sediment composition can be compared to field measurements.

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