CROSS-SHORE GRADED SEDIMENT TRANSPORT: GRAIN SIZE AND DENSITY EFFECTS

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Abstract

Sediment sorting processes (sorting on grain size and density) are the result of local hydrodynamic conditions. In this paper two measuring techniques are described which derive *in situ* time dependent and time averaged distributions of sediment sorted on grain size and density. The technique on measuring grain size of the sediment is described in more detail. The sediment distributions give information on the local hydrodynamic conditions on different time scales. Measurements from the field serve as a test case of describing the depth of closure from measurements of sediment composition.

Introduction

Coastal sediments are rarely composed of one type of sediment. Grain sizes may vary from cobbles, gravel and coarse sand to fine sand, silt and clay; densities show variations from about 1.6 kg l^{-1} for certain carbonates to heavy minerals as dense as cassiterite (7.4 kg l^{-1}). Seldomly however, one observes all varieties mixed at one localised spot. Variations in currents, waves and/or wind tend to concentrate certain sediments at specific locations according to the hydrodynamic properties of a sediment. In turn the variations (gradation) in grain size and density reflect the changes in transport conditions.

Sorting occurs due to differences in settling and pick up of grains with different size, density and shape. In settling the fall velocity of grains is determined by an equilibrium between gravity and friction forces, depending on the size, density and shape of the grain. In entrainment, sorting is due to differences in the exposure of the grain to the fluid and gravity acting on the grain.

Figure 1 presents fall and entrainment velocities as function of grain size and density. The upper part of Figure 1 shows that with small grain sizes, density

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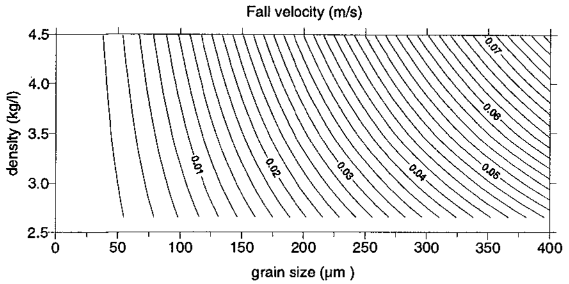
variations have little impact on the fall velocity of a grain (Cheng, 1997) but with increasing grain size, density effects become more important. The lower part shows the critical peak value of the orbital velocity near the bed needed to entrain a grain as a function of density and grain size, based on the formula given by Komar and Miller (1975). For small grain sizes, changes in the entrainment velocity are small with varying density, but for larger grain sizes (>100 μm) density is the most important parameter determining the entrainment velocity.



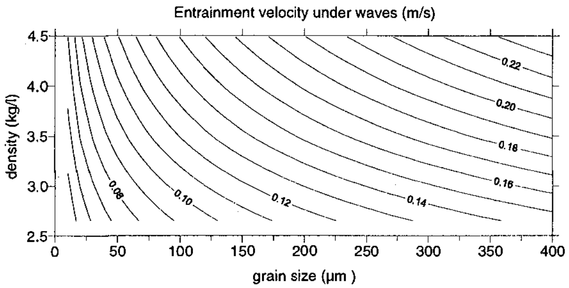


Figure 1: Settling velocity and entrainment velocity ($m\ s^{-1}$) as function of grain size and density.

A comparison between both figures shows that settling and entrainment processes are affected differently by grain size and density variations. Whilst grain-size variations will have a larger effect on the settling velocity, variations in density will have relatively larger effects in the entrainment velocity.

Already in 1949, Inman pointed out that the effects of sorting, reflected in the median grain diameter of the sediment may give information on the conditions under which the sediment was transported and deposited. Also other studies have been conducted describing hydrodynamic conditions based on sediment distributions. Veenstra and Winkelmolen (1976) describe size, shape and density sorting patterns of sediments of the coast of Dutch the barrier island of Ameland, which is also object of study in this paper. Their data show that in the offshore area (deeper than 12m) a coarse sediment population is the result of an earlier high-energy situation during the post-glacial transgression and can not been transported under present hydrodynamic processes. The sediments between this offshore area and the beach show a rather narrow size spectrum and sorting occurs mainly on density and shape.

Studies on the relation between size gradation and hydrodynamics were carried out by various authors (e.g. Guillén and Hoekstra, 1996, Swift *et al.*, 1971).

Guillén and Hoekstra describe a model of the equilibrium distribution of grain-size classes across the cross-shore coastal profile of the Dutch barrier island Terschelling (adjacent to Ameland). They state that the shape of the grain-size distribution curve depends on the hydrodynamic processes acting on the profile and serves as a fingerprint of the system. They observed that the median grain size of the sediment and the distribution of grain-size fractions show a break in their cross-shore distribution at approximately 6m depth across the shore face of Terschelling. This depth is considered to be the closure depth of the profile because it corresponds to the seaward limit of the shallowest and high mobility part of the littoral profile during the studied period.

Hallermeier (1981) extensively describes the expected maximum water depth for significant effect on the sand bottom by surface waves (later referred to as closure depth). In his description, he takes account of sand characteristics and wave parameters to calculate a seaward limit of intense sediment transport and extreme bottom changes. The concept is based on the observation that cross-shore sediment transport decreases seaward and becomes almost negligible beneath a certain depth (closure depth). Since this depth of closure is dependent on the movement of sediment, the position of the depth of closure along the cross-shore profile is a function of density, grain size, shape and time. Figure 2 schematically indicates the shore profile and the border of initiation of motion (depth of closure) as function of grain size and density. Large, heavy grains are harder to transport than small, light grains and, for equal wave conditions, the initiation of motion occurs at a shallower water depth, higher on the profile. Similarly heavier grains have a shallower closure depth than light grains of the same diameter. Investigations of selective transport processes of heavy minerals under shoaling waves (Tánczos (1996), May (1973), Stapor (1973)) showed that selective transport processes are rather rule than exception and start directly at the initiation of motion of sediments. Therefore, measurements of changes in sediment gradation provide information on the initiation of motion.

Measurements of sediment characteristics in the field to determine hydrodynamic conditions have been conducted since 1949 (Inman, 1949). However, these measurements lacked high spatial resolution and were too time consuming for regular measurement campaigns. With the techniques described in this paper, high-resolution *in situ* measurements can be conducted and makes an approach of describing hydrodynamic conditions from sediment characteristics fruitful.

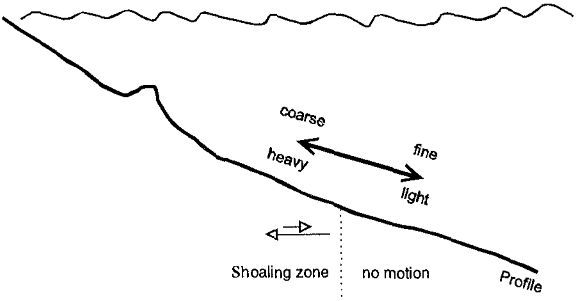


Figure 2: The seaward limit of significant sediment transport is dependent on grain size *and density.*

This paper presents variations of grain size and density along profiles in the field and in the laboratory. The data consist of high density, *in-situ* measurements of grain size and density using a towable seabed detector MEDUSA (de Meijer *et al*, 1996 and de Meijer, 1998). The grain size and density variations are derived from the intensity of friction sound and natural radioactivity. The sensor that utilises the relation between friction-sound and grain size will be explained in more detail. Data is collected on the foreshore of the Dutch Frisian Island of Ameland and in the Großer Wellenkanal (GWK) in Hannover, Germany. The aim of the present study is to measure sediment distributions to extract information on the local hydrodynamic conditions on different time scales. Measurements from the field serve as a test case of describing the depth of closure from measurements of sediment composition.

Experimental techniques

The heavy mineral concentration of the sediments in the field survey is determined from the concentrations of the naturally occurring radionuclides of the decay series of ^{238}U and ^{232}Th. In heavy minerals, the concentrations of ^{238}U and ^{232}Th are two orders of magnitude higher than in light minerals. Although the actual concentrations of ^{238}U and ^{232}Th depends on the mineral composition of the heavy mineral suite, it was found that the heavy minerals near the Dutch Frisian Islands have a quite constant radiometric fingerprint (de Meijer *et al*, 1990, de Meijer and Donoghue, 1995). The total concentration of heavy minerals (THM) is hence calculated from the values listed in de Meijer *et al* (1990). The radiometric variations in the sand of the flume at GWK are not related to the heavy mineral concentration only, but also to grain-size variations (Figure 3). Figure 3 shows a decreasing activity concentration of ^{40}K as function of grain size whereas there is no clear difference in the average activity concentration of ^{40}K in the light and heavy fraction. The ^{238}U+^{232}Th activity concentration also decreases with increasing grain-size, but here the light and heavy fractions differ two orders of magnitude in the ^{238}U+^{232}Th concentration. The grain size dependence of the ^{238}U+^{232}Th concentration may also reflect the grain size distribution of the heavy fraction.

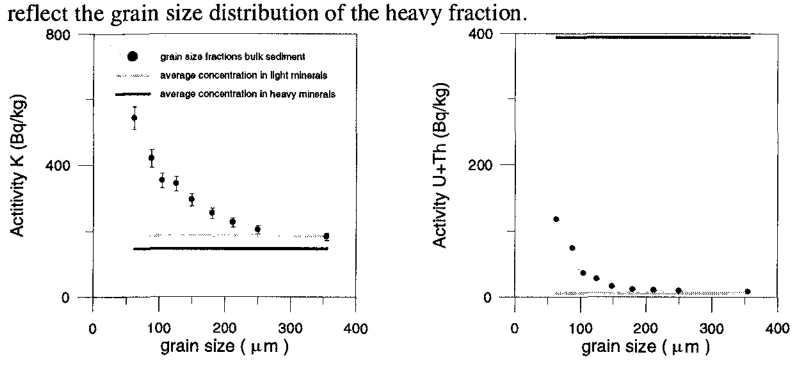


Figure 3: Activity concentrations of 40K, 238U and 232Th as a function of grain-size compared to the average concentrations in the light and heavy mineral fractions.

Measurements with the MEDUSA detector system were carried out at GWK, Hannover and the seafloor near the Island of Ameland. Natural radioactivity is measured with a highly sensitive gamma-ray detector in the standard set-up as described in de Meijer (1998) and the system yields activity concentrations of the three nuclides as long as it is in contact with the bed.

The measurements of friction-sound were carried out with a microphone inside the detector casing. The microphone records noise that the detector generates when the casing slides over the sediment. It was originally included in the detector system together with the water depth sensor to monitor the contact of the detector with the sediment, but the signal variations proved to be consistent with grain size variations and reproducible during several surveys. This triggered the question which variations caused the changes in sound level. Part of this paper deals with the interpretation of the friction-sound measurements and the data of the experiments in the GWK will show that the friction sound level is indeed a quantitative indicator of grain-size variations on the bed.

The experiments in the Large-scale Wave Flume (300×5×7 m^3) (Grosser Wellenkanal Hannover) in Germany were conducted as part of the EU MAST-III-program SAFE. In these experiments, profile development and sediment transport under storm conditions were studied. The sediment was rather coarse (d_{50}=280μm) and not well sorted (d_{10}/d_{90}=3). For the wave conditions, a TMA –wave spectrum with H_m=0.9 m and T_m=6 s was used that was repeated after every 0.5h. The experiments started with a smooth-bed profile with a slope 1:20 and with a water depth of 5m.

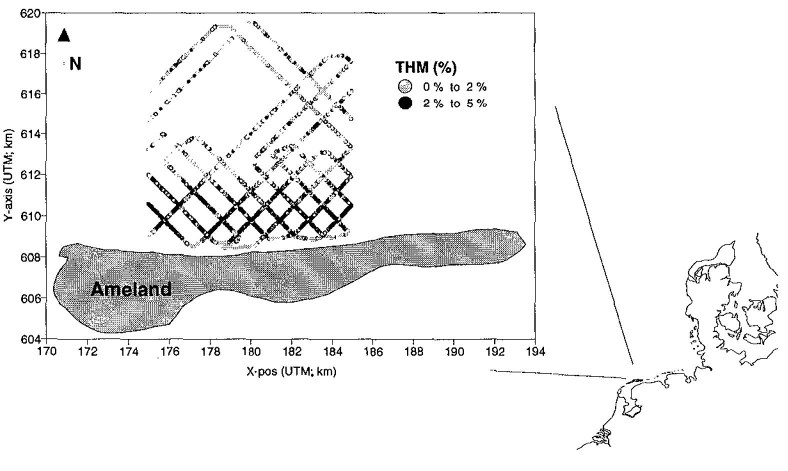


Figure 4: Geographical location of Ameland and an overview of lines towed near Ameland and of the concentrations of total heavy minerals (THM) along these lines. The map is given in UTM co-ordinates.

Results

Seafloor mapping

In June-July 1995, a survey was carried out using a MEDUSA- detector system towed by a vessel of Rijkswaterstaat. During this survey lines were towed between position RSP18 (beach pole 18) on Terschelling and the eastern tip of Ameland at depths of 1-25m. The barrier island Ameland is located in the northern part of the Netherlands just north of the Dutch Wadden Sea and flanked on both sides by a tidal inlet (Figure 4). The near-shore zone of Ameland is characterised by the presence of a bar system with an overall slope between the high water line and the off shore of about 1:400.

This paper presents the data collected in an area between the two ebb-tidal deltas in front of the coast of Ameland.

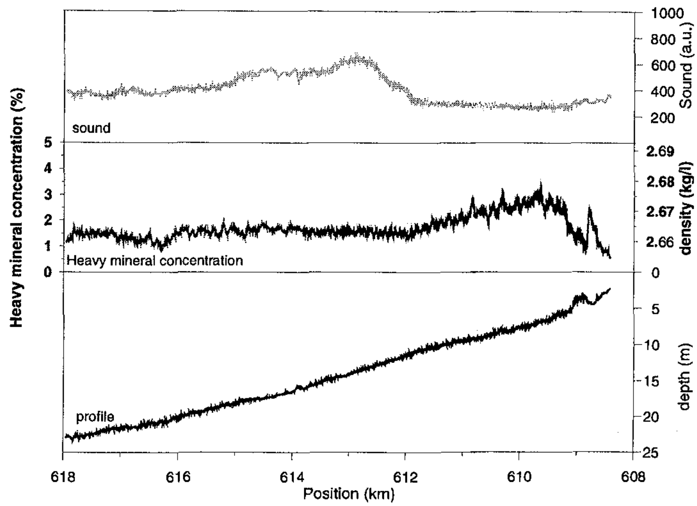


Figure 5: Average profile, heavy-mineral concentration and sound-level variations as function of distance to the coast of Ameland.

Figure 4 shows the distribution of total heavy mineral concentrations (THM) along the towed lines. A coast-parallel region of high concentrations of heavy minerals (up to 5% by mass) is visible a few kilometres off the coast. Seawards of this region the heavy mineral content of the sediment decreases. The heavy-mineral concentration seems to be constant in long shore direction. This distribution triggers the question if the concentration of heavy minerals is solely the result of cross-shore processes.

The mean of all survey data is presented as a cross-shore distribution in Figure 5. In the lower part of the figure, profile data show the position of a breaker bar at a water depth of 2.5-5m and a rather concave seaward slope with a slight convex "bump" between 610 and 613 km. At a position of 611.5 km, the slope steepness seems to increase. The heavy-mineral concentration (middle figure) shows an increased concentration just landwards of the breaker bar, a steep decrease on the breaker bar and again an increase up to position 609.8 km. From this position, the heavy-mineral concentration shows a decreasing trend to position 612 km, where it remains constant towards deeper water. The sound level shows a rather low, constant signal from the breaker bar towards position 612 km. From hereon the sound level doubles in intensity towards position 613 km, followed by a decreasing trend further seawards.

In the case of the heavy minerals of Ameland the density and grain-size distributions were measured by Tánczos (1996): $\rho_{50} = 3.5$ kg/l and $d_{50} = 110$ μm. Taking the density of quartz sand to be $\rho_q = 2.65$ kg/l, the heavy-mineral concentrations are converted to bulk densities. The corresponding values are indicated in the right-hand scale. From the figure one notices that small changes in density can be measured.

It is remarkable that large variations in sound level and heavy mineral concentrations occur in the region of convex bump in the profile. Seawards from this position, the heavy mineral concentration remains constant, while the recorded sound levels show an increase.

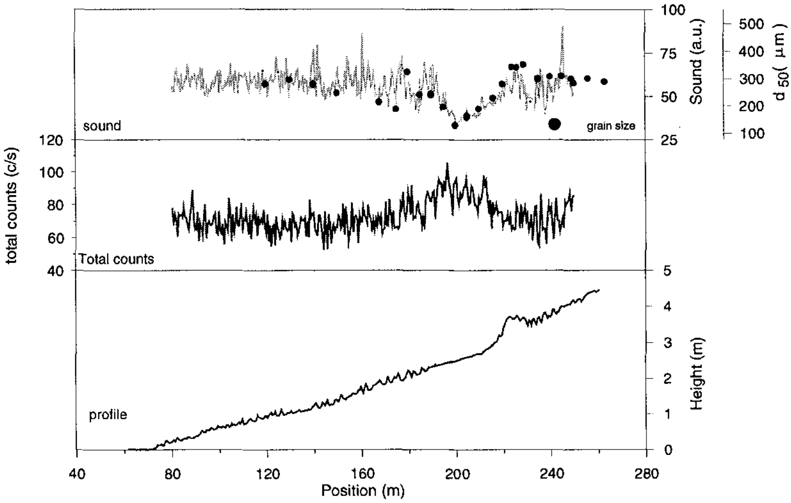


Figure 6: Profile, heavy mineral concentration and sound level distribution after 17h of storm conditions in the laboratory experiments at GWK, Hannover.

Laboratory experiments

The wave conditions of the experiments in the GWK were planned to be erosive at the beach face and during the experiment, a breaker bar developed at x=220m and at a water depth of 1-2m (Figure 6). "Seawards" of the breaker bar, the morphology is characterised by a smooth region without ripple structures, followed by a region with relatively large ripple structures. Again, MEDUSA is used to derive sediment characteristics along the profile.

For the sand in the flume the activity concentrations are very low and the total count rate rather than the individual radionuclide distribution is presented. The total count rate on the breaker bar is lower compared to other parts of the profile. Seawards from the breaker bar, the total count rate increases. In the smooth region, where the ripple structures are absent, the total count rate shows a maximum. In the region with ripple structures, "seawards" from the "flat zone" the count rate remain constant. The sound level shows variations that are almost opposite to the heavy-mineral concentration pattern. The sound level is high on the breaker bar, shows a decrease in the region where the ripple structures are absent, increases and remains constant towards deeper water. It is remarkable that the scatter in sound level is low in the region where ripples are absent.

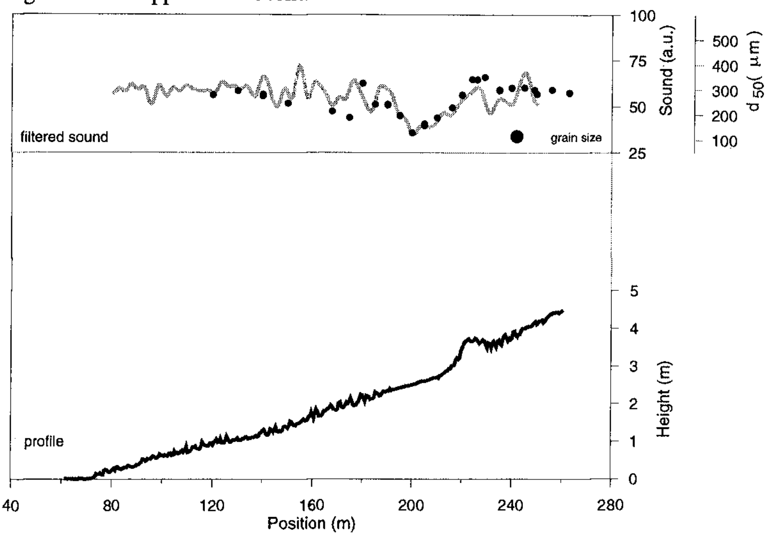


Figure 7: Profile, filtered sound level and median grain size *(d_{50}) after 17hrs of storm conditions in the laboratory experiments.*

<u>Assessment of the relation between friction-sound and grain size</u>

To investigate a possible relation between sound level and grain size of sediment, samples of the sediment top layer were collected at various locations of the bed after the water was drained from the flume. After drying and sieving, the grain-size distribution was derived. The d_{50} values are presented in the top part of Figure 6 together with the sound-intensity level. The two data sets show a remarkable correspondence in behaviour; the more because the sound level is likely produced by the upper grains of the sediment whilst, even in careful scooping of sediment, layers of several millimetres thick are collected.

A statistical analysis of the correlation between grain-size and sound level measurements of three different datasets from the wave flume experiments, show a significant correlation (r^2=0.7, with 41 degrees of freedom). To test the importance of grain size in the measured sound levels, two samples of sediment from the profile, with different sound-level characteristics, were glued on a wooden plate over which the detector was towed. Since the measurements with the calibration plate were conducted out off the water and the acoustic properties of the plate and natural sediment are different, only relative values may be compared. This small experiment confirms that larger grain sizes show larger sound levels than smaller grain sizes.

Table1: Sound levels of two types of sediment with different grain size. *Statistical uncertainties, 1 STD, are given in brackets.*

Grain size (µm)	Sound level wooden plate (a.u.)	Sound level sediment (a.u.)
265	167 (18)	53 (4)
380	210 (20)	69 (3)

The sound level exhibits a spiky behaviour, mainly, in the region of the ripples; in the smooth region and on the "seaward" part of the breaker bar such spikes are hardly present. A fourier transform was applied to filter small scale variations in the sound level (<5 metres) from the signal, testing the hypothesis that small scale variations are correlated to ripple structures. Figure 7 shows the filtered signal in comparison with the d_{50} value. Apparently, the small-scale variations on the sound level do not have an influence on the large-scale trend of sound level. It seems that the large-scale trend in sound level reflects the grain-size variations of the bed while sound level variations correlated with small-scale changes in morphology (like ripple structures) are superimposed on this trend. Whether these small-scale variations are directly the result of "bumping" on morphologic features or arise from the grain-size variations due to sorting within ripple structures is not clear.

Synthesis

It is remarkable that on the coast of Ameland large variations in radiometry and sound level occur in the region of the convex bump in the profile. Seawards from this position, the heavy mineral concentration becomes constant, while the sound level shows an increase. These changes in sound, which are related to grain size, and THM are probably caused by a difference in sediment population compared to the sediments near shore. During the fast sea level rise after the last glacial period, the barrier islands showed a fast landward retreat and part of the profile was "overstepped". This lower part of the profile shows sediments that are sorted by hydrodynamic conditions that are different from present day hydrodynamics. Since the transgression slowed down, the sediment distribution could come in equilibrium with present day hydrodynamic conditions (Veentra and Winkelmolen, 1976; Guillén and Hoekstra, 1996) and sediments could be sorted by grain size, density and shape. The change in slope steepness of the profile reflects the change between the relict profile from the transgressive phase and the "recently" reworked part of the coastal rofile (Swift, 1971).

During the process of coastal retreat, the recently reworked part of the profile eroded older sediments and heavy minerals remained as a lag deposit. The increase in heavy mineral content from the concave bump up to the breaker bar is probably the result of sorting of these lag deposits by processes due to wave shoaling (Tánczos, 1996; May, 1973). The constant sound level shows that the grain size is rather constant in this region and sorting will mainly occur on density and shape. Landward of the bar system the heavy mineral content increases while the breaker bar itself is depleted of heavy minerals. Here light sediments are transported and build the breaker bar, while heavy minerals remain in the eroding parts as lag deposits.

To compare the sediment distributions on the profile of the field measurements and the laboratory experiments, the sediment characteristics are plotted as a function of a scaled dimensionless waterdepth in Figure 8. The dimensionless waterdepth is derived by dividing the waterdepth by the maximum wave height. In the upper left part of Figure 8, a clear change in heavy-mineral grading occurs at a $d/H_{max} \sim 2$. Seaward from this location, the heavy-mineral concentration is constant, while the concentration shows a landward increase. It is remarkable that this depth (11m) coincides with the long-term closure depth (9-11m) for this region calculated from wave data (Westlake, 1995).

Experiments on graded sediment transport showed that sorting occurs at the initiation of motion. At a water depth >11m, sediment is not transported and sorting does not occur, while at shallower waterdepths, light minerals start to move and heavy minerals remain as a lag deposit or are transported at smaller transport rates. A this location where light minerals start to be transported, sorting is initiated. In the lower left part of Figure 8, a similar behaviour of sediment sorting can be observed. At a d/H_{max} >2 sediment composition is constant, while at shallower depths sediment sorting is initiated. The sorting pattern from the laboratory experiments is solely generated by cross-shore sediment transport processes. Since this pattern is comparable with the measurements of the seafloor, it seems that the sediment distribution on the seafloor is predominantly the result of cross-shore processes.

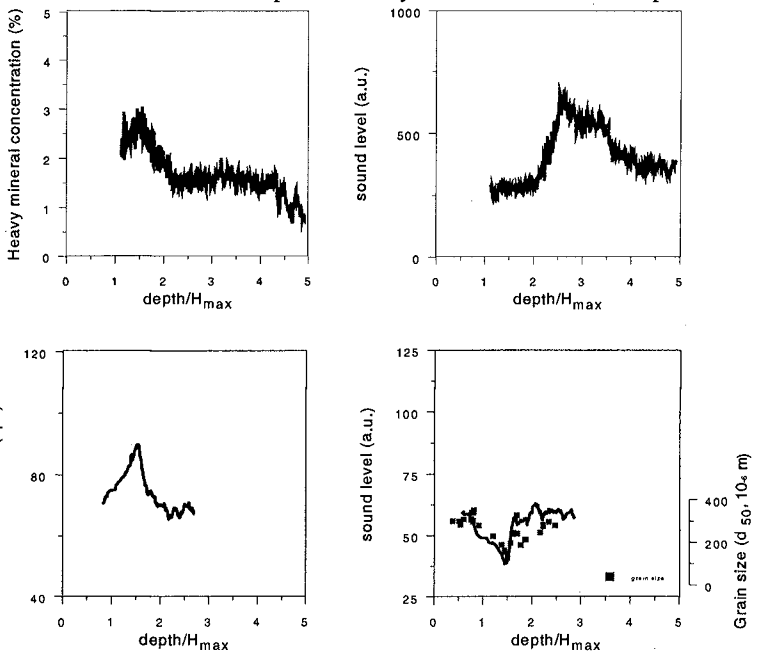


Figure 8: Heavy-mineral concentration and sound level variation as a function of depth/H_{max} from the Ameland survey (upper graphs) and total count rate, sound level and grain-size distribution (squares) as a function of depth/H_{max} from the laboratory study (lower graphs). The lines represent a running average fit trough the data points.

For the GWK measurements a major change in sound level can be observed at a d/H_{max} ~2. This depth was indicative for the depth of initiation of motion. However, sound level variations for the field survey are somewhat different from the sorting patterns measured with radiometry. Here, the large sound levels at d/H_{max} >2 are the coarse relict sediments of the transgressive phase while the lower sound levels at d/H_{max} <2 reflect sediments that are sorted by present day processes.

Both measuring techniques give different information on the depth where significant sorting processes start. The radiometric measurements comprise the upper 20 to 30cm of the sediment bed (maximum penetration depth of γ-radiation in sand)

and will therefore describe time scales of at least a few weeks, while the measurements of sound level only describe the upper grains of the sediment bed. The results of the laboratory study have shown that sorting of the upper layer of the sediment reach equilibrium for the specific wave conditions in a few hours. Therefore, the sound level measurements reflect only a local closure depth on a very small time scale.

Conclusions

Measurements on the seafloor near Ameland and measurements in the flume at GWK, Hannover show corresponding (scalable) distribution patterns of sediment sorting by density and grain size. The wave-flume experiments indicate that these distributions can be predominantly the result of cross-shore hydrodynamic processes. Heavy minerals tend to be concentrated seawards of the bar system in a region of fine-grained sediments just landward from where sediment motion is initiated.

The technique of deriving grain size by measuring the friction noise of the MEDUSA detector seems promising and would allow a synoptical, in-situ measurement of grain-size parameters. Together with the measurement of heavy-mineral content by means of natural radioactivity, MEDUSA allows the measurement of as well density and grain size. These two sedimentological parameters play an important role in sediment transport processes. Applying these techniques both in the field and the laboratory offers a handle to study these in more detail in laboratory experiments and in the field.

The results from the present investigation suggest that by the applied methodology the depth of initiation of motion can be measured in the field for different time scales.

Outlook

Further research on the correlation between friction-sound measurements and grain size will focus on frequency dependent sound measurements. At the moment, friction-sound measurements comprise a summation of all the sound frequencies. A sensor for measuring frequency specific friction-sound will be tested. For a refining of the sediment distributions in the radiometric measurements of the wave flume, a refinement of the fingerprint of the sediments will be conducted to allow a clear distinction between heavy mineral and grain-size distribution. Therefore the heavy and light sediment fractions will be split into separate grain-size fractions and measured for its radionuclide content.

Acknowledgements

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