Selective Sediment Transport in the Nearshore Zone: Field Observations and Potential Mechanisms

Piet Hoekstra and Klaas T. Houwman

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Netherlands Centre for Coastal Research

Institute for Marine and Atmospheric Research Utrecht
Utrecht University, P.O. Box 80.115, 3508 TC Utrecht, The Netherlands.

Selective Sediment Transport in the Nearshore Zone: Field Observations and Potential Mechanisms

Piet Hoekstra[1] and Klaas T. Houwman[1]

Abstract

Field observations of selective sediment transport in the nearshore zone are reported from Terschelling, The Netherlands. The results are based on the developments prior to and shortly after the implementation of a shoreface nourishment. Selective sediment transport mechanisms are discussed and appear to be related to combinations of all major sediment transport components.

Introduction

Sediment properties have since long been recognized as being an important factor in sediment transport processes and, as such, may play an important role in coastal morphodynamics. Especially the sediment fall velocity or equivalent grain size is a relevant parameter in this respect. From studies in the past, it is a well known fact that the order of magnitude of sediment transport substantially varies for different (median) grain sizes. A coarsening of the sediment, for example, results in a decrease of the mobility of the sand grains in relation to the criterion for the initiation of motion and, in case of highly graded sediments, may also lead to a certain degree of armouring of the bed. In addition, not only the order of magnitude but also the (net) direction of the transport seems to change, e.g. due to a different relative contribution of (wave-dominated) bedload versus (longshore current-dominated) suspended load transport (Van Rijn, 1995).

One has also noticed that there may be a differential behaviour of grain size fractions under the same hydrodynamic conditions. This differential behaviour is observed in response to either a natural range in overall settling velocities of the sediment (e.g. Guillen and Hoekstra, 1996) or, more specifically may result from a variability in the specific density of the sediment due to mixtures of light and heavy minerals (Tanczos, 1996).

Research Objectives

In the following section a brief description of the main results of the NOURTEC field experiment of Terschelling (The Netherlands) is given, demonstrating the different responses of various grain size fractions in the nearshore zone after the introduction of a perturbation in the sediment grain size composition due to the implementation of a shoreface nourishment. The main objective of the present study is to evaluate and

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[1] Institute for Marine and Atmospheric Research, Utrecht University, P.O.Box 80.115, 3508 TC Utrecht, the Netherlands, e-mail: p.hoekstra@frw.ruu.nl

understand the principal sediment transport mechanisms that are expected to be responsible for the observed selective sediment transport in the nearshore zone.

NOURTEC Observations of Selective Sediment Transport

In the spring and summer of 1993, a shoreface nourishment was carried out along the barrier island coast of Terschelling, the Netherlands (Hoekstra et al. 1997). The shoreface nourishment formed part of a larger international (EC-MAST2) experimental programme, called NOURTEC, to study the feasibility, effectiveness and optimum design characteristics of shoreface nourishment techniques in different marine environments. The Terschelling shoreface nourishment was located offshore, in the depth interval between -5 and -7 m below NAP (Dutch Ordnance Datum), filling up the trough between two nearshore and (almost) shore-parallel breaker bars. Sediment sampling was carried out in various campaigns prior to (March 1993 - T0) and after the nourishment (November 1993 - T1, April and October 1994 - T2 and T3, respectively). In total, more than 1000 samples were collected and elaborated. Sediment sampling procedures, grain size and data analysis are presented by Guillen and Hoekstra (1996).

Prior to - but also after - the nourishment a clear overall trend was found in the cross-shore distribution of median grain sizes (Fig. 1). The median grain size reaches a minimum (150-160 micron) at about 6 to 8 m depth and shows a coarsening in both a landward and seaward direction. The coarsest sediment is located on the intertidal beach and in the swash zone and the median grain size of this sediment locally varies from

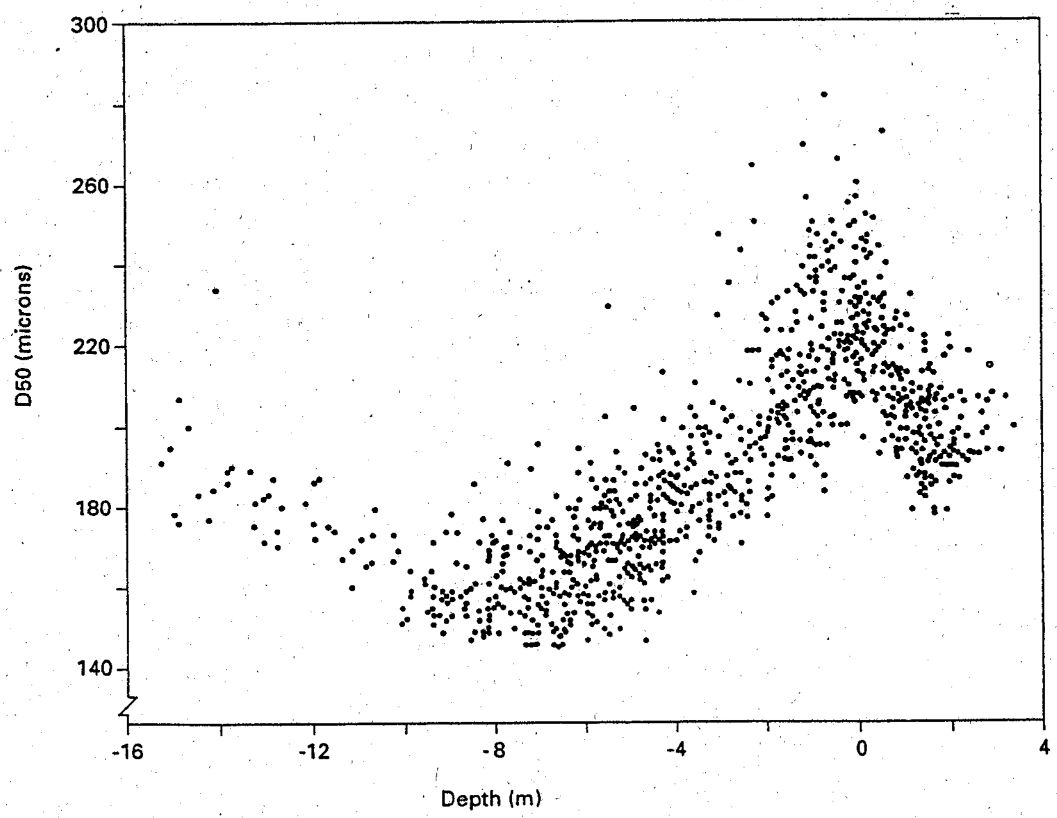

Figure 1. Cross-shore variation of median grain size with depth for all samples taken in the Terschelling study area (based on 4 sampling campaigns).

200-260 micron; on the beach the D_{50} reduces again towards the dune foot. The general patterns that emerge are the result of the underlying, overall distribution in grain size fractions in the nearshore zone. As a matter of fact, also the cross-shore distribution of grain size fractions shows a clear relation with depth (Guillen and Hoekstra, 1996). For example the finest fractions (100-150 and 150-200 micron, respectively) display a maximum in the relative distribution at 6-8 m depth; in general almost 50-60 % of these fractions, present in an individual cross-shore profile, is found in this zone.

The nourished sand differed in two ways from the native, local deposits at the nourished site (Guillen and Hoekstra, in press):

- the nourished sand was in general coarser than the native deposits (Fig. 2); consequently, the nourished area was characterized by an overall coarsening of the sediment with more than 20 micron (Fig. 2) in comparison to the original deposits (the actual range in coarsening varied locally from about 15 to 60 micron);
- the nourished sediment was more poorly sorted than the native deposits.

In general, there is a very rapid response of the grain size characteristics immediately after the implementation of the nourishment. About half a year after the nourishment an overall fining is observed in the area of the nourishment (Fig. 2). Most of the sediment is about 15 micron or more smaller than in the previous post-nourishment situation and grain sizes are comparable again with those observed during the pre-nourishment conditions (Fig. 2). This fining is mainly related to a loss of the coarser fractions (> 200 micron). Meanwhile a coarsening is observed closer to the beach, especially due to the increase of the fraction 200-250 micron. However, whether this material is actually originating from the nourishment or just another zone, is unknown. A longshore origin is not expected, given the longshore uniformity in sediments (next sections). The differences in median grain size between the T2 (April 1994) and T3 (October 1994) campaigns are only marginal (Fig. 2) and a (seasonal ?) fining is observed in a longshore-oriented zone close to the beach, in an area West, East and landward from the nourishment. The finest fractions of the nourishment (100-150 micron) though tend to be dispersed into an offshore and Eastward direction (Guillen and Hoekstra, in press); the latter direction is corresponding with the dominant wave- and wind-driven longshore drift (Hoekstra et al., 1997).

Summarizing the results, the natural (cross-shore) patterns in grain size characteristics, the onshore coarsening of the sediment and the offshore and longshore dispersion of fine-grained deposits (100-150 micron) after the nourishment demonstrate that fine and coarse grain size fractions behave differently under the same hydrodynamic conditions. The natural distribution of median grain sizes and the related grain size fractions, as well as the rather quick "recovery" of the former pre-nourishment grain size distribution indicate that there is an optimum, depth-dependent interval for the presence of specific grain size classes (and, logically the associated D_{50}). The time-averaged and remarkably stable character of this distribution directly implies that selective sediment transport mechanisms have to be operating in the nearshore zone.

A further analysis of wave- and current-driven sediment transport processes is carried out in order to identify the (potential) processes and mechanisms that are responsible for selective sediment transport across the (upper) shoreface. In a first approach, only cross-shore sediment transport processes are taken into account, since the cross-shore grain size distribution along the barrier island coast of Terschelling shows a great longshore uniformity (Guillen and Hoekstra, in press; see also partly Fig. 1).

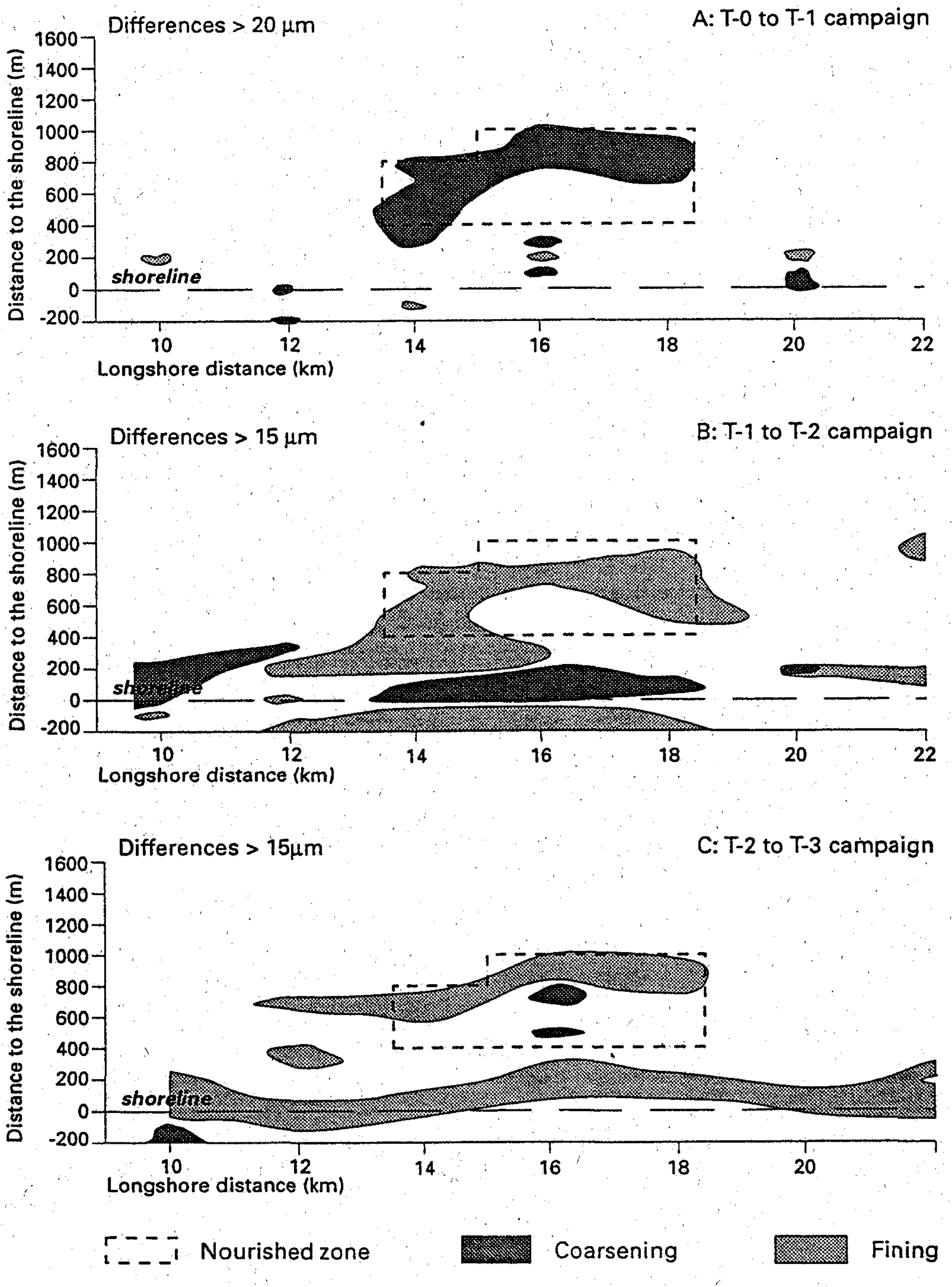

Figure 2. Coarsening and fining inside and outside the nourished area of Terschelling.

Selective Sediment Transport Mechanisms

The total cross-shore sediment transport in the nearshore zone is commonly decomposed into bedload and suspended load components. Suspended load components may be further subdivided in current-dominated fluxes due to mean flows (such as a cross-shore directed undertow or a rip current) and oscillatory fluxes related to high- and low-frequency waves. As a result one can easily distinguish a number of the most obvious combinations of sediment transport mechanisms that can lead to selective sediment transport and a segregation of grain size fractions for graded sediments:

1: *Onshore bedload transport* due to wave asymmetry and streaming versus *offshore suspended load transport* due to mean currents;

2: *Onshore directed suspended load* transport due to *wave asymmetry*, in combination with *offshore directed suspended load* transport due to mean currents (*undertow*);

3: Alternating *onshore* and *offshore* directed *oscillating suspended load* transport.

Mechanism 1. This is one of the mechanisms emerging from the spatially varying pattern of grain size characteristics prior to and shortly after the execution of the shoreface nourishment. The field observations at the NOURTEC site suggest that the greater part of the finer sediments has predominantly been transported as suspended load in both an offshore and longshore direction. The offshore transport is expected to be the result of undertow, probably in combination with suspension fall-out from rip currents. Meanwhile, according to the morphological evolution since the nourishment, a substantial amount of nourished sediment has also moved in an onshore direction (Hoekstra et al., 1997). This material may partly represent the coarser bedload fractions of the nourished sediment which, in combination with oscillatory suspended load, is thought to be transported onshore in response to a landward-directed wave-asymmetry (and streaming).

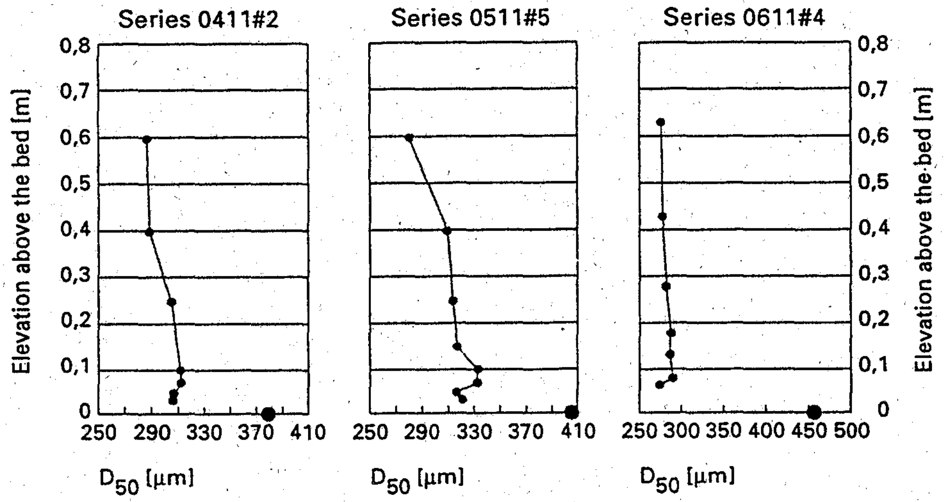

Figure 3. Grain size variation as a function of height above the bed for bedload and suspended load (time-averaged samples).

Therefore, for the proposed mechanism there basically are two requirements to generate selective sediment transport: 1) *opposing* flow/transport directions for bedload and suspended load, and 2) natural *vertical* gradient in grain size for suspended load relative to bedload. The first condition is easily satisfied for irregular and natural breaking waves in the surfzone. A mixture of breaking and non-breaking waves leads to a simultaneously existing breaker-induced undertow and the presence of highly asymmetric waves. Hydrodynamic and sediment transport measurements at the NOURTEC - site clearly confirm the co-existence of both processes (Houwman and Ruessink, 1997; Hoekstra et al., 1997; see also next section on mechanism 2). For the second condition though, no data is available from the NOURTEC site and information is based on field observations at the Egmond aan Zee experimental site, along the West coast of the Netherlands (courtesy of Wolf, 1997). A comparison of the grain size characteristics of time-averaged suspended load samples and bedload samples, taken in the inner nearshore zone of Egmond aan Zee for conditions with breaking waves, shows a considerable range in median grain size (Fig. 3). On average, the D_{50} of the bedload is more than 80 micron coarser than the suspended load. This rather extreme difference between bedload and suspended load may be due to the fact that the samples were taken in an area relatively close to the beach. In conclusion, the processes of onshore bedload transport due to wave asymmetry (and streaming) versus offshore suspended load transport due to mean currents will certainly contribute to the effect of selective sediment transport.

Mechanism 2. In the surfzone, for conditions with breaking waves, suspended load transport is commonly dominant and bedload usually represents only a minor part of the total sediment transport (Van Rijn, 1995). However, as demonstrated by Houwman and Ruessink (1997), this bedload component may still be significant in determining the net sediment transport magnitude and direction. Their results show that the onshore directed oscillating suspended load transport is more or less equal to and balanced by the offshore directed mean suspended load transport. Therefore, the contribution of a minor transport component may still be relevant in these conditions. Part of the approach of Houwman and Ruessink (1997) is adopted in this paper to evaluate the impact of grain size characteristics on both suspended load components. A sensitivity analysis is carried out by applying the *modified* Van Rijn/Ribberink model (Van Rijn, 1993) for sediment transport computations. Since this approach does not include the oscillating suspended load transport - the suspended sediment is only transported by mean currents - the model has been modified to incorporate the oscillatory fluxes (Houwman and Ruessink, 1997). In addition, the original model required the input of a depth-averaged mean velocity and a wave height. Instead of this, a second modification was implemented and the model is now run with timeseries of measured near-bed velocities - so including measured wave-orbital velocities - and water levels. As a result, the modified sediment transport model computes the bedload, transported by both waves and currents, the oscillating suspended load transport and the mean suspended load transport.

During the NOURTEC experiment of Terschelling a number of process-oriented measuring campaigns have been carried out. Each campaign lasted for a period of about 6 weeks (Hoekstra et al., 1997). Data from these measurements are used in the present analysis. As an illustration of the procedure, data are taken from a tripod (F3), located at the seaward side of the outer bar at an average depth of about 5-6 m.

The following procedure is applied:

1) Sediment transport computations are performed with the locally measured time series of waves and currents and by using the local native, median grain size (here: 165 micron);
2) Sediment transport fluxes are related to the ratio of local wave height and local water depth (Hm0/h): the transport fluxes are represented and classified as a function of this relative wave height Hm0/h (see Fig. 4);
3) The long-term or annual *Probability density function (Pdf)* of the relative wave height (P{Hm0/h}) is determined; the long-term contribution of the sediment transport fluxes is calculated for each class of Hm0/h by multi-plying the corresponding sediment transport fluxes with the related *Pdf*;
4) The final result is a diagram representing the magnitude and direction of the various sediment transport components as a function of relative wave height and frequency of occurrence, the "yearly mean transport rates" (Houwman and Ruessink, 1997; Fig. 4, right panel; positive transport means onshore, negative is offshore).

The results depicted in Fig. 4 first of all indicate that both suspended load components indeed largely exceed the bedload component. Secondly, the mean suspended load component is offshore directed (undertow), whereas the oscillating component is entirely onshore directed (wave asymmetry; the flow measurements do not include streaming effects). Finally, the mean suspended load component is in general larger than the oscillating component. It means that for this particular example, the ratio of offshore directed and onshore directed suspended load components is larger than one. As a next step in the analysis, the sediment transport computations are repeated for different local median grain sizes. The left panel in Fig. 4 shows similar computations at location F3, but now for a median grain size of 100 micron. The result is a considerable increase in sediment transport rates for the different components as well as a changing relative contribution of offshore versus onshore directed suspended load fluxes.

This can be further illustrated by normalizing the ratio for "equilibrium" conditions with a median grain size of 165 micron. By definition, in these conditions (D_{50} = 165 micron) the ratio is made equal to unity, corresponding with no net transport (Fig. 5). Likewise, for another median grain size the ratio of offshore versus onshore directed suspended load fluxes is normalized by using the ratio in "equilibrium conditions". The results are presented in Fig. 5; position F2 is located on the shoreface, at an average depth of about 9 m. For both positions F2 and F3 the general trend is quite obvious: if sediments are smaller than the average local grain size the offshore directed transport processes are dominating. A coarsening of the sediment results in the opposite effect and onshore directed transport processes are prevailing. The main reason for this effect is the changing relative contribution of both suspended transport components with height above the bed. The lower part of the suspension vertical is dominated by the oscillating suspended transport whereas at greater heights above the bed, the mean suspended transport is the dominant component. A decrease in local grain size leads to increasing suspended sediment concentrations, in particular at greater heights above the bed. Consequently, both the oscillating and mean suspended transport will increase. In reponse to the vertical distribution though, the latter transport component will increase more rapidly than the former one. Therefore, a local coarsening is in favour of onshore transport whereas a local fining promotes the offshore transport. This is in general in line with the results of the NOURTEC grain size study.

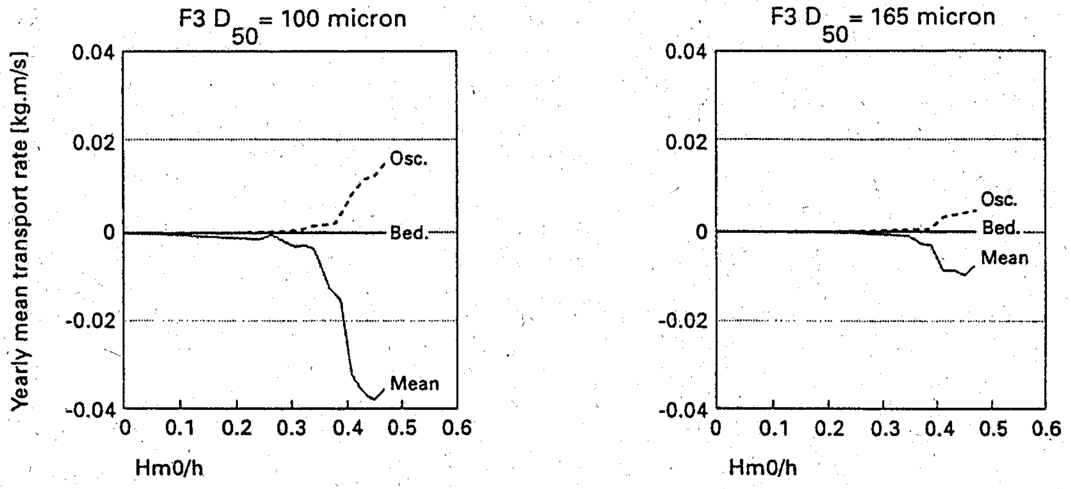

Figure 4. The effect of median grain size (D_{50}) on the computed cross-shore suspended load components at location F3 for native deposits (D_{50} = 165 micron; right panel) and finer sediments (D_{50} = 100 micron; left panel).

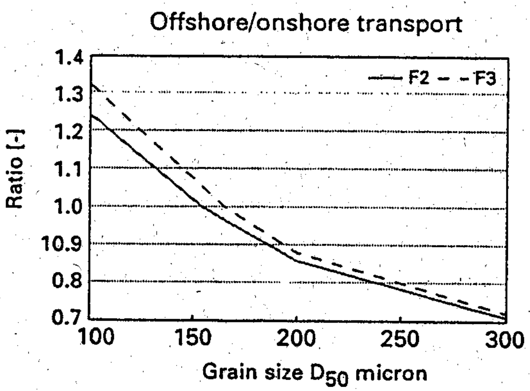

Figure 5. Ratio of onshore and offshore directed yearly suspended load transport at locations F2 and F3 as a function of local median grain size (for computational procedures see text).

Mechanism 3. Another potential mechanism for the segregation of grain size fractions and selective sediment transport is the net result of the oscillating suspended load transport. In general the net result of the alternating onshore and offshore directed oscillating suspended load components greatly depends on the degree of wave asymmetry and the existence of time lag effects between the high-frequency velocity and concentration signals. An impression of these time lag effects can be obtained by plotting the mean (high-frequency) shape of the orbital velocities and concentrations, showing the mutual phase relationships (procedure of ensemble-averaged signals). Shortly after the nourishment, during the T2 measuring campaign (Spring 1994) and as observed for only a restricted number of measurements, there appears to be a considerable time lag between orbital velocities and concentrations. Onshore orbital velocities coincide with low concentrations (Fig. 6) whereas the transition from onshore to offshore orbital flow marks the development of a sharp concentration peak. Surprisingly enough, a level of higher concentrations is maintained during the offshore directed orbital flows (Fig. 6). As a result a net offshore directed oscillating flux will be observed. In the past, a significant time lag effect is frequently explained by the presence of bedforms. A ripple-induced vortex is developed during onshore flow and, together with suspended sediment, is being lifted from the bed during flow reversal. During the offshore directed flow, the associated sediment is partly being moved and gradually settles (e.g. Horikawa, 1988).

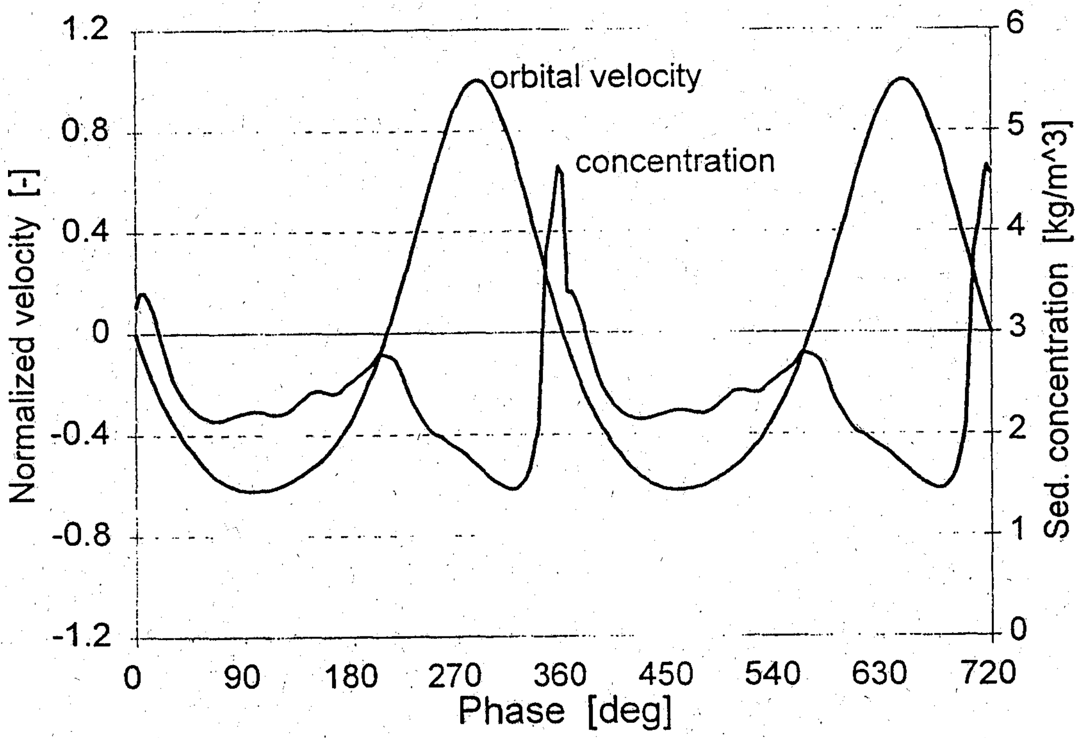

Figure 6. Average wave shape and concentration showing time lag effects for suspended sediment concentrations relative to wave orbital velocities; relatively high concentrations are observed during offshore directed orbital velocity components.

However, another possible explanation for the features observed in Fig. 6 could be the relative abundance, at that stage in the post-nourishment situation, of relative fine sediment fractions. The extreme peak in concentration during flow reversal may be associated with a wave bottom boundary layer shear instability in relation to this flow reversal, as described by e.g. Foster et al. (1994). The finer suspended sediments are distributed across the vertical and start to settle again but as long as the settling time is larger than the average half wave period (0.5T), the concentration just gradually diminishes. This may cause a dominantly seaward directed, oscillating flux of fine grained sediments. Given the present lack of information concerning the grain size characteristics of instantaneously suspended sediments and the (unknown) origin of concentration peaks around flow reversal, for the time being, the latter explanation can only be considered as a hypothesis.

Conclusions

The result of the NOURTEC field study leads to the inevitable conclusion that selective sediment transport processes are operating in the nearshore zone. Consequently, for naturally graded coastal sediments, the use of a single grain size parameter to represent the sediments - for example, as applied in sediment transport formulae - becomes less meaningful or even questionable. Without any doubt, the mechanism of onshore bedload transport due to wave asymmetry and streaming versus offshore suspended load transport due to mean currents (undertow) is an important mechanism responsible for this selective transport. Based on a sensitivity analysis with the modified Van Rijn/Ribberink model, the combination of onshore directed suspended load transport due to wave asymmetry and offshore directed suspended load transport due to mean currents may be a second important mechanism. Alternating onshore and offshore directed oscillating fluxes, in particular in relation to fine-grained sediments and the occurrence of phase lag effects between velocities and concentrations, represent a third potential mechanism although this effect is extremely difficult to prove.

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