Sediment sorting at a large scale nourishment
A comparison of field data of the Sand Motor area and a model study of sediment sorting in the cross-shore direction

E.E. Sirks
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MASTER OF SCIENCE THESIS

For the degree of Master of Science in Hydraulic Engineering at Delft University of Technology

E.E. Sirks

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The undersigned hereby certify that they have read and recommend to the Faculty of Civil Engineering and Geosciences for acceptance a thesis entitled

**Sediment sorting at a large scale nourishment**

by

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A new approach in coastal maintenance is the application of a large scale nourishment as natural feeder of the coast. The Sand Motor constructed near Kijkduin on the Holland Coast is a pilot project of this new nourishment strategy. An accurate prediction of the development of large scale nourishments like the Sand Motor is of importance as future large scale nourishments can then be designed more efficiently.

The objective of this research is to contribute to a better understanding of the sediment transport processes at nourishments by analysing the sediment sorting processes. The main research goals are to determine the sediment sorting in the Sand Motor area and the parameters influencing the sediment sorting processes in the cross-shore direction.

The Sand Motor is used as a case study to research the sediment sorting in a large area without the influence of native sediments. The sediment composition in the Sand Motor area is analysed based on sediment samples of a few measurement campaigns, both before and after the construction of the Sand Motor. The research differentiates in longshore and cross-shore sediment sorting. A numerical model (Delft3D) is used to simulate the sediment sorting processes and time scales in the cross-shore direction at a large scale nourishment. The bed stratigraphy module of Delft3D is used to track the development of sediment sorting in several layers. The wave roller module of Delft3D is used to introduce realistic waves in the model without the use of Delft3D-WAVE. The initial bathymetry and initial sediment composition of the nourishment were varied to research the effect on sediment sorting. Furthermore the effect of different wave conditions was researched.

The measurement data showed an increase of the sediment sorting in the longshore direction. The median grain size at the Sand Motor was on average about 100 $\mu m$ larger than the median grain size in the area North of the Sand Motor. It is hypothesised that the fining North of the Sand Motor is caused by the deposition of relatively fine material that is eroded at the Sand Motor. A measured decrease of the uniformity at the Sand Motor is in accordance with this hypothesis.

In the cross-shore direction the minimum median grain size in the transects was found to move seaward after the construction of the Sand Motor. It is assumed that the wave conditions preceding these measurements influenced the location of the minimum median grain size.

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Higher wave conditions are assumed to lead to a minimum median grain size located further offshore due to the stronger undertow.

The used cross-shore model represents the measured sediment sorting qualitatively, as the general trend of the sediment sorting is the same and the location of the minimum median grain size appears to be related to the wave height. However, the model does not reproduce the coarsening of the sediment composition at about 8m water depth. The model results show a strong influence of the sedimentation and erosion in the profile on the sediment sorting pattern. This pattern is found to be independent of the initial bathymetry and initial sediment composition of the nourishment. It is shown that extreme wave heights have a large influence on the sediment distribution in the profile as wave conditions determine the area where sediment sorting takes place. Furthermore, the sediment distribution also responds more quickly to higher waves.

Finally, the hypothesis is confirmed that the location of the minimum median grain size in the profile is dependent on the wave conditions. Model results show that the location of the minimum median grain size is located at the edge of the morphologically active profile and is thus related to the wave height via the closure depth formulation.

To conclude, this research consists of new measurement information on the sediment composition in the Sand Motor area and a comparison of this data set with existing measurement campaigns. This information shows the influence of the Sand Motor on the alongshore and cross-shore sediment sorting and states the influence of the wave conditions on the location of the minimum median grain size in the profile. The model results show the use of a relatively simple Delft3D model to study the influence of different parameters on the sediment sorting processes and the timescale of these processes.

Recommendations for further research include to investigate what caused the trend difference between the model results and the measurements at the Sand Motor. And finally, it would be valuable to continue to measure the sediment composition at the Sand Motor. Performing a measurement campaign twice a year is recommended to study both the influence of extreme events as the long-term development of the sediment composition.
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This thesis is the result of the MSc research project into sediment sorting processes at the Sand Motor. The thesis is written in partial fulfillment of the Master of Science degree in Hydraulic Engineering at the faculty of Civil Engineering and Geosciences of Delft University of Technology.

First of all I would like to thank Bas Huisman, my daily supervisor, for his enthusiasm, dedication and valuable feedback and advice. I would like to thank the other members of my graduation committee: Professor Stive, Joep Storms and Dirk Jan Walstra for their showed interest in the topic and their feedback during the committee meetings.

Taking sediment samples at the North Sea in February would have been less succesfull without the help of Saulo Meirelles Nunes Da Rocha and Matthieu de Schipper. Thank you both for your time and trouble to help out at the last moment. I would also like to thank Daan Wouwenaar, the captain and shipper of the boat who made an effort to get the boat at the exact GPS location and was also skillfull enough to let us sample in the breakerzone.

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In the first month of my research project I was invited to go to the NCK days organised by the Netherlands Centre for Coastal Research with a poster on the performed measurement campaign. I am thankful for the given opportunity to meet people who are working or researching in the field of coastal engineering and hear about the current research.

The mayor part of my research project I have conducted at Deltares surrounded by a large group of Master students. I would like to thank Deltares for the possibility to carry out this research at Deltares, the facilities were good and I have enjoyed the attendance of the lunch lectures especially. Thanks to all the master students at Deltares for the fun times, the sharing of knowledge and the mental support. I would also like to thank the employees at Deltares who showed an interest in my work.
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Delft,  
27th September 2013
This chapter introduces the problem definition and the motivation for research. Subsequently the research questions are presented to tackle a part of this problem in this thesis as well as the followed approach. Finally the thesis outline briefly describes the content of the different chapters in this thesis.

**Problem definition**

Nourishments are an important mean to maintain the position and safety levels against flooding. The size of a commonly used shoreface nourishment requires repetition of the application of a nourishment every 5 years. A new approach in coastal maintenance is the application of a very large nourishment as natural feeder of the coast. The natural forces (e.g. waves, currents) will redistribute the sediment over a larger coastal area. Near the coast of Kijkduin (The Netherlands) a large hook-shaped peninsula was created with sediment dredged offshore. This large scale nourishment, called the Sand Motor, is a pilot project for this new coastal maintenance strategy. An accurate prediction of the development of large scale nourishments like the Sand Motor is of importance as future large scale nourishments can then be designed more efficiently. This saves money, allows for better planning of coastal maintenance and improves beach safety.

More knowledge on sediment transport processes at a nourishment could be obtained by researching the sediment sorting at a nourishment. Sediment sorting is defined as the spatial variation of grain size parameters. The sediment sorting at a nourishment is expected to be a representation of the sediment transport processes at a nourishment, as the sediment transport depends on the grain size. The Sand Motor project is used as a case study in this research to see whether and how the sediment of a nourishment is sorted, what processes are important in the redistribution of sediment in the cross-shore direction and what the time scales are of these processes. The scale of the Sand Motor gives the opportunity to research the redistribution of a known sediment type (the nourished sediment) in a large area, without influence of the native sediments. Furthermore, the initial sediment composition of the Sand Motor can be assumed to be uniformly distributed.
Research questions

The greater objective of this research is to contribute to a better understanding of the sediment transport processes at nourishments. This MSc thesis focusses on the sediment sorting at the Sand Motor and the sediment sorting processes in the cross-shore direction. The following questions are investigated and answered in this thesis:

1. How is the nourished sediment sorted at and around the Sand Motor?
2. What influences the sediment sorting processes at a nourishment in the cross-shore direction?

The part of the coastal zone that is researched is the nearshore zone ranging from the waterline till a water depth of about -11 m NAP. The considered sediment consists of non-cohesive particles classified as sand, with grain sizes between 63-1000 µm. Aeolian transport and effects of aspects of ecology (e.g. benthos) on the sediment transport are not taken into account.

Approach

First, a literature study is performed to gather information on sediment transport mechanisms related to sediment sorting, the sediment composition along the Holland Coast and the sediment sorting at nourishments.

Measurement results of field data on the sediment composition in the Sand Motor area is collected from different organisations. An additional data set is acquired by an own dedicated field campaign in the area. These data sets are analysed and the results are compared to map the development of the sediment distribution.

A cross-shore model of a large scale nourishment is developed in the numerical model Delft3D. The model represents the Sand Motor in some aspects though it lacks structural erosion, bar morphology and hiding and exposure processes. However, the model can be used to research the effect of different environmental parameters on the sediment distribution and the timescales of the sediment sorting processes.

Thesis outline

The outcome of the literature study into the sorting of sediment is presented in Chapter 2. This literature treats the driving mechanisms of sediment sorting, the sediment composition along the Holland Coast and the sediment sorting at nourishments. Chapter 3 describes the Sand Motor design, the hydrodynamic conditions and modelled sediment transport processes. The results of the different measurement campaigns are reported in Chapter 4. This chapter first describes the different measurement campaigns and used measurement methods, hereafter the results of these measurement campaigns and subsequently the development of the spatial distribution of grain size parameters in time. The uncertainties in the use of the measurement methods and the use of measurements as such to analyse the sediment composition are discussed before closing the chapter with the most important conclusions and a few
hypotheses on the sediment sorting processes. Chapter 5 presents the results of the model study into the sediment sorting processes in the cross-shore direction. The chapter begins with an introduction of the numerical model Delft3D and an explanation of the set-up of the designed cross-shore model. The main part of the chapter is about the results of the different modelled scenarios that show the effect of environmental parameters on the development of the sediment sorting in the cross-shore direction. The chapter is finished with a discussion of the model results and a conclusion. Finally, the thesis concludes with the most important conclusions and gives a number of recommendations for further research in Chapters 6 and 7.
Chapter 2

Literature review

2-1 Introduction

This chapter contains theoretical information on sediment sorting at nourishments based on a literature study. The basic theory of sediment transport is presented before the sediment transport and sorting processes in the cross-shore direction are looked into. As the Sand Motor is located at the Holland Coast the hydrodynamics of this coast and the sediment transport and grain size characteristics are presented. Finally, the chapter gives some general information about the application and behaviour of nourishments, as well as the results of grain size measurements on a nourishment at Terschelling (The Netherlands). The information in this chapter can be considered as the theoretical basis this thesis is based upon.

2-2 Sediment transport

In this section the basic theory of sediment transport is explained, what this means for sediment transport nearshore in a cross-shore direction and how this influences the distribution of grains of different sizes in the cross-shore direction.

2-2-1 Basic theory of sediment transport

The basic theory of sediment transport is explained starting with (1) how sediment can be characterised by grain size parameters, (2) which forces act on these grains, (3) what force needs to be exceeded to move grains, (4) in what manner these grains can be transported and finally (5) how this leads to a sediment concentration in the vertical.

Grain size parameters

Grain size parameters that can influence the transport are the grain size, the grain shape and the grain density. In this research the focus lies on differences in grain size. The grain shape
and grain density are assumed constant.

The grain size characteristics of a sediment mixture can be expressed with $D_x$, the sediment particle diameter for which $x\%$ by weight is finer, the passing percentage (Bosboom and Stive, 2010). Several $D_x$ values for different passing percentages enhance the knowledge about the sediment composition. The $D_x$ values can be determined based on the sieve curve of the sediment sample, see Figure 2-1. The median diameter, $D_{50}$ is often used together with a measured for the gradation to represent a sediment mixture. Gradation means the spread in particle sizes in the sediment mixture and is expressed as a ratio between a larger $D_x$ and a smaller $D_x$. The used diameters in literature for the calculation of the uniformity coefficient differ, in this thesis the definition of the British Standard is used, presented in Equation 2-1. A well graded sample has a high uniformity coefficient, or with other words: the sediment distribution is ‘wide’, or ‘poorly sorted’ as sediment particles of a large range of sizes are present in the mixture. A poorly graded sample has a low uniformity coefficient and is the opposite of a well graded sample: the sediment distribution is ‘narrow’, or ‘well sorted’ as mainly sediment particles of a narrow bandwidth of grain sizes are present in the mixture.

$$c_u = \frac{D_{60}}{D_{10}}$$

(2-1)

$c_u$ = Uniformity coefficient [-]

$D_{60}$ = Grain diameter at 60% passing percentage [$\mu$m]

$D_{10}$ = Grain diameter at 10% passing percentage [$\mu$m]
Figure 2-1: Sieve curve of sample C05-I. The blue circles are the measured passing percentages corresponding to the sieve sizes, the blue line is the approximated sieve curve used to approximate the nominal diameter per passing percentage. The red dashed line gives an example of the determination of the $D_{60}$. 
Forces on a grain

Sediment particles in the water accelerate until they reach a constant vertical velocity, the fall velocity. This velocity is dependent from the balance between the downward directed gravity force (Eq. 2-2) minus the effect of buoyancy and the upward directed drag force (Eq. 2-3). All these forces are proportional to the grain size: the drag and lift force are proportional to the surface of the grain ($D^2$) and the gravity force is proportional to the volume of the grain ($D^3$). Note that the assumption is made that the grains are spheres, which is actually not the case. The resulting fall velocity (Eq. 2-4) depends both on grain parameters (sediment density in $s$, grain size in $D$) and on the hydrodynamics via the drag coefficient which mainly depends on the Reynolds number (see Figure 2-2).

\[
F_G = (\rho_s - \rho)g(\frac{1}{6}\pi D^3)
\]
\[
F_D = \frac{1}{2}C_D \rho w_s^2(\frac{1}{4}\pi D^2)
\]
\[
w_s = \sqrt{\frac{4(s - 1)gD}{3C_D}}
\]

$F_G$ = Gravitational force on grain [N]
\(\rho_s\) = Sediment density [kg/m$^3$]
\(\rho\) = Water density [kg/m$^3$]
\(g\) = Gravitational acceleration [m/s$^2$]
\(D\) = Grain size diameter [m]
\(F_D\) = Drag force on grain [N]
\(C_D\) = Drag coefficient [-]
\(w_s\) = Fall velocity [m/s]
\(s\) = Relative density of sediment [-]

![Figure 2-2: Variation in drag coefficient with Reynolds number for natural sand. (Fredsøe and Deigaard, 1992)](image)

The drag coefficient can be approximated for certain grain size classes. For small particle sizes (smaller than 0.08 mm) the fall velocity is proportional to $D^2$, for large particle sizes...
(larger than 1.9 mm) the fall velocity is proportional to $\sqrt{D}$. For sand, as it has particle sizes in between 0.08-1.9 mm, the fall velocity is thus in between $D^2$ and $\sqrt{D}$ and empirical formulas can help to determine the fall velocity relation per diameter bosboom2010lecture. With the use of empirical formulas and average conditions a characteristic fall velocity of 0.01 to 0.05 m/s is defined for sand particles of medium size (100 to 500 $\mu m$).

**Initiation of motion**

Sediment particles start moving when the fluid force on a particle is larger than the resisting forces related to the grain size characteristics as weight (from volume and relative density) and friction coefficient. The driving force is mostly based on the near-bed velocities, consisting of turbulent flow velocities, wave orbital velocity and current velocity. The relation between shear stress and shear velocity is presented in Equation 2-5.

$$\tau_b = \rho u_* |u_*|$$  \hspace{1cm} (2-5)

$\tau_b$ = bottom shear stress [N/m$^2$]

$u_*$ = velocity [m/s]

Motion of sediment particles is initiated when the dimensionless bed-shear stress ($\theta$, Equation 2-6) is larger than a threshold value ($\theta_{cr}$, the Shields parameter). The Shields parameter depends on the hydraulic conditions and the particle size and shape. This dependency can be expressed with the grain Reynolds number, a ratio between the inertial and viscous forces on the grains.(Eq. 2-7)

$$\theta = \frac{\tau_b}{(\rho_s - \rho)gD}$$  \hspace{1cm} (2-6)

$\theta$ = dimensionless bed shear stress

$\tau_b$ = bed shear stress [N/m$^2$]

$\rho_s$ = sediment density [kg/m$^3$]

$\rho$ = water density [kg/m$^3$]

$g$ = gravitational acceleration [m/s$^2$]

$D$ = grain size diameter [m]

$$Re_* = \frac{u_* D}{\nu}$$  \hspace{1cm} (2-7)

$Re_*$ = grain Reynolds number [-]

$u_*$ = critical friction velocity [m/s]

$D$ = grain size diameter [m]

$\nu$ = kinematic viscosity coefficient [m$^2$/s]

Shields performed a range of experiments to test the initiation of motion on a flat bed surface, resulting in a curve representing the moment of initiation of motion (2-3), meaning that
a minor part (1 to 10%) of the surface is moving. The Shields parameter signifying the initiation of motion varies between 0.1 and 0.03, for larger grain Reynolds numbers the Shields parameter becomes a constant 0.05 for larger grain Reynolds numbers, see Figure 2-3. The distinction between transport or no transport of grains is often not so black and white as described by the Shields curve. Shields treats the initiation of motion as a discrete threshold-value, though in experiments Davies (1985) demonstrated that for wave-generated near-bed velocities a transitional range of velocities for the initiation of motion was present. And for sediment with a non-uniform grain-size distribution armouring of the bed layer could prevent the initiation of motion of smaller particles.

**Armoured bed layer**

The composition of a bed layer consisting of different sediment fractions can get an armour layer if smaller particles are washed away. Larger particles are not transported and block the smaller particles from the water and prevent erosion of these particles. Due to the armouring effect the larger particles are more exposed and the critical shear stress for transport is lower. The reduced possibility of transport of smaller particles and the increased possibility of transport of larger particles is called the hiding and exposure effect of the armoured layer.

**Modes of transport**

Sediment transport, or the way that sediment particles are transported, can be divided in to three different types, listed here and depicted in Figure 2-4. The total sediment transport can be calculated by calculating the bed load and suspended load separately and adding them together. The wash load is further neglected as this consists of very fine particles that are continuously in suspension.

- Bed load
- Suspended load
- Wash load
Bed load
The bed load transport is defined as the part of the sediment transport that is more or less in contact with the bed during transport. This includes grains that roll, slide and jump along the bed. This transport is activated if the bed shear stress exceeds the critical value. It is assumed that the particles respond instantaneously to a critical bed shear stress. Bosboom and Stive (2010) distinguish sheet flow as a type of bed load transport mode occurring at higher shear stresses (Shields parameters higher than 0.8-1.0). The sheet flow can be observed as the top layer of the bed moving back and forth as a sheet of sand with reversing flow conditions.

The effect of the grain size on the amount of bed load transport is not large, especially in the high velocity range (>0.8m/s)(Van Rijn, 2007a). Van Rijn points out that the bed-load transport formula of Bagnold (1966) does not have the particle size as a basic parameter and that the bed-load transport formula of Meyer-Peter and Müller (1948) is almost independent of particle size in the upper regime far beyond the critical Shields stress. Van Rijn used both results of large-scale wave tunnel experiments of Delft Hydraulics and model computations of different scenarios to show this limited effect of particle size on the bed load transport rate, see Figure 2-5. The bed load transport increases only slightly for increasing particle sizes in the sand range, this is related to the effect of the fluid drag force on the particle in comparison with gravity and friction.

Suspended load
The suspended load is defined as the part of sediment transport that does not have contact
with the bed. The particles are supported by turbulent diffusive forces (Fredsoe and Deigaard, 1992), keeping them from returning to the bed. In contrast to the effect of the grain size on the bed load transport, the grain size has (among other parameters) a strong effect on the amount of suspended load transport (Van Rijn, 2007b). The degree of uniformity of the sand bed influences the suspended sediment transport as well. Van Rijn (2007c) showed that the suspended load transport above a graded bed increases by a factor of 2 to 3 compared with that above an almost uniform sand bed.

The amount of suspended load is a product of sediment concentration $c$ and horizontal velocity $u$ of the water (Bosboom and Stive, 2010). The suspended load transport does not respond instantaneously to the hydrodynamic conditions, because the particles take time to settle (Bosboom and Stive, 2010). The velocity and the sediment concentration vary strongly in time, over each wave period and depending on the tidal period and wind conditions for example. In engineering applications the wave-averaged velocity distribution and sediment concentration are often used. The resulting sediment transport is illustrated in Figure 2-6.

![Figure 2-6: Distribution of the horizontal velocity, sediment concentration and sediment transport in the vertical. Bed load transport takes place in a thin bed load layer close to the bed (between $z=0$ and $z=a$). The suspended load transport takes place in the upper layer. (Bosboom and Stive, 2010)](image)

**Sediment concentration**

The sediment concentration in the vertical profile is of importance to calculate the suspended sediment transport rate as described in the previous section. The advection-diffusion relation of sediment (Eq. 2-8) can be set-up based on the mass balance for sediment and the decomposition of the velocity terms in a mean, oscillatory and turbulent part. The horizontal advection terms are neglected and the turbulent velocities are averaged (Reynolds’ averaging). The fall velocity is assumed constant. The variation of the concentration in time depends on the net amount of sediment going downward with the fall velocity and the net amount of sediment going upward with the fluid turbulence.

$$\frac{\partial c}{\partial t} - w_s \frac{\partial c}{\partial z} + \frac{\partial \langle c'w' \rangle}{\partial z} = 0$$  \hspace{1cm} (2-8)

The turbulence term $\langle c'w' \rangle$ can be rewritten using the turbulence diffusivity of sediment mass $\nu_{t,s}$ which is usually taken equal to the turbulent viscosity of the water $\nu_t$. The turbulent motion in the water transports water with a higher concentration of sediment upwards and water with a lower concentration of sediment downwards, leading to a net upward directed transport.
\[ c = \text{sediment concentration (turbulence averaged)} \ [m^3/m^3] \]
\[ t = \text{time} \ [s] \]
\[ w_s = \text{fall velocity} \ [m/s] \]
\[ z = \text{vertical distance} \ [m] \]
\[ \langle c'w' \rangle = \text{(upward sediment) flux by turbulence} \ [m/s] \]

\[ -\langle c'w' \rangle = \nu_{t,s} \frac{\partial c}{\partial z} \]  

(2-9)

\[ \langle c'w' \rangle = \text{(upward sediment) flux by turbulence} \ [m/s] \]
\[ \nu_{t,s} = \text{turbulence diffusivity of sediment mass} \ [m^2/s] \]
\[ c = \text{sediment concentration (turbulence averaged)} \ [m^3/m^3] \]
\[ z = \text{vertical distance} \ [m] \]

Rouse suggested a parabolic distribution over the vertical for the turbulence diffusivity of sediment mass, using the Von Karman constant:

\[ \nu_{t,s}(z) = \kappa u_* \frac{z}{h}(h - z) \]  

(2-10)

Integration of Equation 2-8 over the depth leads to Equation 2-11.

\[ w_s C(z) + \nu_{t,s}(z) \frac{dC(z)}{dz} = 0 \]  

(2-11)

As a boundary condition near the bed the concentration at the top of the bed load boundary layer (at \( z = a \)) is used:

\[ C_a = \frac{S_b}{ua} \]  

(2-12)

The result is a concentration distribution over the depth, dependent on the Rouse number. The Rouse number is a non-dimensional number, the ratio of downward sediment fall velocity and upwards velocity on the grain based on \( \kappa u_* \). The Rouse number determines the mode of transport: for Rouse numbers larger than 2.5 all transport is bed load transport, for Rouse numbers smaller than 0.8 all transport is wash load, and in between suspended transport occurs.

\[ C(z) = C_a \left[ \frac{h - z}{z} \frac{a}{h - a} \right]^{zs} \]  

(2-13)

\[ zs = \frac{w_s}{\kappa u_*} \]  

(2-14)

### 2-2-2 Cross-shore sediment transport

The sediment transport in the cross-shore direction is explained starting with (1) how the grain size influences the equilibrium profile, (2) how the active profile is dependent on the extreme wave conditions, (3) what transport components are present in the cross-shore direction and (4) how this influences the typical cross-shore morphology.
Equilibrium profile

Profiles are expected to have or move towards a profile shape for which the profile is in equilibrium. The steepness of this equilibrium profile depends on the sediment characteristics of the material on the bed. Bruun (1954) was the first to propose this relation (Eq. 2-15) based on measured beach profiles along the Danish North Sea coast and the California coast.

\[ h = A(x')^m \]  

\( h \) = Profile height from reference plane [m]  
\( A \) = Shape factor [-]  
\( x' \) = Distance from waterline [m]  
\( m \) = factor = \( \frac{2}{3} \) [-]

Dean (1977) has shown, based on linear wave theory, that Bruun’s formula is consistent with uniform wave energy dissipation per unit volume within the surfzone. With the assumption of shallow water and a simple dissipation model for the surfzone, Dean (1987) showed that the A shape factor is related approximately linearly to the fall velocity on a log-log plot, see Figure 2-7 and Equation 2-16. The grain size at the beach thus influences the equilibrium beach profile via the fall velocity. Beaches with coarser sediment imply a larger value of A, and thus a steeper beach profile and the opposite holds for beaches consisting of smaller sized sediment.

\[ A = 0.5w_s^{0.44} \]  

\( A \) = Shape factor [-]  
\( w_s \) = Fall velocity [m/s]

With an analytical approach Doering and Bowen (1988) derived expressions for equilibrium profiles by balancing onshore and offshore transport components for the middle and lower
shoreface. The resulting equilibrium profile (Eq. 2-17) for shallow water resembles the formulas of Bruun and Dean, with a profile shape factor of \( A = 0.16 \) (Bosboom and Stive, 2010). The dependence of the profile shape on the grain size diameter is in the fall velocity.

\[
h \approx \frac{7.5w_s^2}{g^{3/2}x^3}
\]  

(2-17)

**Closure depth**

The equilibrium profile approach can be applied to the morphologically active part of the profile. This active zone extends from the first dune or cliff face to a little offshore of the end of the surfzone. The seaward limit of the active profile is called the closure depth. This closure depth is located a little offshore of the end of the surfzone. The theory and different equations to determine the closure depth are listed in this section.

Hallermeier (1978, 1981) defined the closure depth as the limit of intense bed activity. He formulated Equation 2-18 for the closure depth (\( h_* \)) based on correlations with the Shields parameter (for bed activity).

\[
\frac{\rho v_b^2}{(\rho_s - \rho)gh_*} \approx 0.03
\]  

(2-18)

\[
\begin{align*}
\rho & = \text{Water density} \ [\text{kg/m}^3] \\
v_b & = \text{Amplitude of wave-induced bottom velocity} \ [\text{m/s}] \\
\rho_s & = \text{Sediment density} \ [\text{kg/m}^3] \\
g & = \text{Gravitational acceleration} \ [\text{m/s}^2] \\
h_* & = \text{Closure depth} \ [\text{m}]
\end{align*}
\]

Hallermeier (1981) transformed this equation in a more applicable form using an ‘effective’ significant wave height \( H_e \) (via Equation 2-20), as that height which is exceeded only twelve hours per year (0.14% of the time), because the closure depth is associated with wave conditions that are relatively rare.

\[
h_* = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right)
\]  

(2-19)

\[
\begin{align*}
h_* & = \text{Closure depth} \ [\text{m}] \\
H_e & = \text{Effective significant wave height} \ [\text{m}] \\
g & = \text{Gravitational acceleration} \ [\text{m/s}^2] \\
T_e & = \text{Wave period associated with } H_e \ [\text{s}]
\end{align*}
\]

\[
H_e = \bar{H} + 5.6\sigma_H
\]  

(2-20)
\[ H_e = \text{Effective significant wave height [m]} \]
\[ H = \text{Annual mean significant wave height [m]} \]
\[ \sigma_H = \text{Standard deviation in wave height [m]} \]

Birkemeier (1985) adjusted the constants in Hallermeier’s formula based on higher quality field measurements (Eq. 2-21) and he also suggested a simplified approximation with nearly the same quality of fit to the data (Eq. 2-22).

\[
h_s = 1.75H_e - 57.9\left(\frac{H_e^2}{gT_e^2}\right) \tag{2-21}
\]
\[
h_s = 1.57H_e \tag{2-22}
\]

The above analysis of the extent of the active profile and the formulation of the closure depth is used by Stive et al. (1992) to determine the cross-shore spreading of nourished sediment. Stive et al. (1992) extended Hallermeiers formulation to longer time scales by replacing the significant wave height exceeded 12 hours per year by the significant wave height exceeded 12 hours per y year. With the use of this concept the position of the nourishment foot can be determined, and this foot will only move further outward for extreme wave height conditions. Transport to a depth larger than the depth of closure is observed in the case of beach nourishments, where the steep initial slope can cause transport to greater depths due to the effect of gravity. Browder and Dean (2000) showed this larger depth of closure with data of Perdido Key (Florida).

**Transport components**

The sediment transport in the cross-shore direction is a mix of bed load and suspended load transport mainly caused by the vertical velocity profile generated by waves. Van Rijn (1997a) lists the following aspects that induce transport components in the nearshore zone in the cross-shore direction:

- **Short wave asymmetry (Stokes drift)**
  Due to non-linearity, the orbital velocity under short waves is asymmetric; the velocities under wave crests are higher than those under the troughs. This leads to a large transport term directed onshore.

- **Undertow**
  The undertow is an offshore-directed velocity to compensate for the positive mass flux by the waves (the Stokes drift). The undertow transports sediment offshore, especially in storms a lot of sediment is transported offshore.

- **Longuet-Higgins streaming**
  The onshore directed streaming in the wave boundary layer generates transport onshore.

- **Long-short wave interaction**
  Due to long-short wave interaction outside the breaker zone the long-wave velocity is directed offshore when the highest wave occur, causing a net offshore transport (Shi and Larsen, 1984).
Gravity

Gravity induces transport of sediment particles on sloping beds in the downward direction.

**Figure 2-8:** Measured velocities under a propagating wave. The shoreward velocity due to short wave asymmetry, the undertow and the Longuet-Higgins streaming are measured relative to the average velocity. (Bosboom and Stive, 2010)

The magnitude of the cross-shore velocities in the vertical of the first three listed wave components is visualised in Figure 2-8. Roelvink and Stive (1989) made a quantitative comparison of the magnitude of the contribution of the above mentioned components to the total cross-shore transport along the Holland Coast (Figure 2-9). The total transport is directed offshore, consisting of onshore transport by the short wave asymmetry, offshore transport by the return flow (undertow) and the transport by the long wave contribution, varying to onshore transport in the surfzone. The influence of the gravity on the sediment transport is neglected in this analysis.
Figure 2-9: The total third and fourth odd flow moments and their constituent components in the cross-shore. Model predictions (lines) and measurements (crosses) of cross shore sediment transport components. (Roelvink and Stive, 1989)
Cross-shore morphology

The profile of a coast is influenced mainly by waves. In a coastal environment like the Dutch Coast high energy waves create a dissipative beach profile. This means that the beach is wide and flat with one or multiple linear bars and with dunes backing a wide beach. The typical surfzone of a dissipative beach is wide, and high energy waves start breaking far offshore (Bosboom and Stive, 2010). In summer, with milder conditions, a steeper more reflective beach profile is set. Storm events reshape the profile to the winter profile again.

A breaker bar is developed at the point where offshore transport stops and becomes onshore transport, this point is located at the end of the surfzone ((Fredsoe and Deigaard, 1992), see Figure 2-10).

![Figure 2-10: Sediment transport in cross-shore direction related to the point of wave breaking, creation of breaker bar (Fredsoe and Deigaard, 1992)]

2-2-3 Sediment sorting in the cross-shore profile

The transport processes in the cross-shore direction will cause sorting of sediment when the sediment composition of the bed consists of several sediment fractions, as the grain size influences the sediment transport (see Section 2-2-1). In this section the current theories and measurement results on the spatial and temporal sediment sorting in the cross-shore of an eroding profile will be presented.

Sorting processes

The sorting process is dependent on sediment characteristics (size, shape and density) as well as the hydrodynamics. Four basic processes of selective sorting on beach sediments are (e.g. Komar et al., 1989; Hughes et al., 2000; Osborne and Simpson, 2005)

- Settling equivalence
  Larger grains of lower density are deposited at the same time as smaller grains of higher density (Rubey, 1933). This process is not relevant in this research as the density of all grains is assumed equal. With equal density grains the larger grains will settle faster than the smaller grains as the fall velocity of larger grains is larger.
• Selective entrainment
Smaller and heavier particles are difficult to entrain with larger and lighter particles (Komar and Wang, 1984). This process is equivalent to the mentioned armouring effect of entrainment of smaller particles by larger particles, preventing erosion of smaller particles.

• Selective transport
Particles are carried by a flowing fluid based on their position in the flow.

• Shear sorting
Coarser grains tend to move upward in the vertical to zones of lower shear, while finer grains move downwards to the zone of maximum shear (Bagnold, 1954).

Spatial sorting
In general sediment nearshore is found to be relatively coarse, and the sediment size decreases in offshore direction. The asymmetric Stokes-wave results in a shoreward movement of coarse particles and a seaward movement of fine particles, as the high velocities (of short duration) move suspended sediment shoreward, coarse sediment settles and finer sediment stays in suspension and is transported offshore with the longer offshore direction flow related to the orbital motion of the Stokes-wave. This theory by Cornish (1898) is verified by Bagnold (1940) with experiments and modeled with some succes by Horn (1992). The high grain size nearshore decreases up the foreshore, as the intensity in the swash zone decreases (Osborne and Simpson, 2005).
Çelikoğlu et al. (2006) found an accumulation of finer material at the crest of the newly formed profile, with a well sorted sediment composition (small $c_u$). On both sides of the crest of the bar the sediment was observed to be armoured. At the toe of the bar profile they found a larger grading of the sediment. These observations were made in a laboratory experiment with regular monochromatic waves of $H_0=5.8$ cm and $T=1.6$ s. Because of the scale of the laboratory experiment the sediment transport consisted mainly of bed load transport.

Temporal sorting
The time scale of sediment sorting can be as small as half a wave cycle in the swash zone according to Clifton (1969), where every wave changes the sediment composition of the top layer. At longer timescales, the preceding extremer conditions such as a storm with high waves or spring/neap tide variations can alter the shape and location of the beach profile and influence the distribution of sediments. A longer timescale based on seasonality also influences the sediment sorting, as the grain size changes with approximately the same period as the profile according to the research of Medina et al. (1994). The researched profile of El Puntal, Santander on the Atlantic Ocean coast of Spain takes about four months to change from summer profile to winter profile and about eight months to change the other way around. The variability of the sediment sorting in time is showed to be dependent on the variation of the morphology by Medina et al. (1994). At the location in the profile where the morphologic change is the largest, the variability of sediment parameters at this location is the largest as well.
2-3 Holland Coast

This section describes the way sediment is sorted along the Holland Coast. The hydrodynamic conditions and the type of sediment are discussed first, then the sediment transport processes and rates, afterwards a conclusion can be drawn on the sediment sorting processes along the Holland Coast.

2-3-1 Hydrodynamic conditions along the Holland Coast

The coastal climate of the Holland Coast is of importance for the sediment transport conditions along the coast. Therefore a short overview on the wave and tidal climate and the way the Holland coast can be characterised is written here.

Tidal climate

The tidal character of the Holland Coast can be characterised by the tidal range and the tidal character. The tidal regime based on the tidal range is based on the mean spring tidal range: the difference between spring high water and spring low water. According to Eisma (1968) the tidal range along the Holland coast varies from 2.3 m at Den Helder to 1.95 m at the Delfland coast and Hook of Holland. (see Figure 2-11). Janssen (2005) mention a difference in high and low-water levels of 1.4 to 3.8 meters along the entire Dutch Coast. Wiersma and Van Alphen (1988) mention a tidal range of 1.7 m at Hook of Holland and 1.4 m at Den Helder. A tidal range lower than 2 meter is considered as micro-tidal according to Davies (1964). Though Janssen (2005) refers to the Dutch Coast as a coast with a meso-tidal regime, probably because some of the values of the tidal range given above refer to the mean tidal range and not the mean spring tidal range.

The tidal character is based on the relative influence of the different components of the tide, the tidal constituents. The most important tidal constituents along the Holland Coast are the semi-diurnal components of the sun and the moon: S2 and M2. The diurnal components K1 and O1 have less influence. The resulting tide along the Holland Coast is classified as semi-diurnal: twice a day there is a maximum (flood) water level and minimum (ebb) water level due to the tide. One of these maxima and one of these minima are slightly more extreme due to the declination of the earth.

The propagation of the tide is influenced by the rotation of the earth, this forces the tidal wave to deflect to the right in the Northern Hemisphere. The land masses in the North Sea area force the tidal wave to propagate anti-clockwise around two nodes where there is no tidal amplitude, so-called amphidromic points, see Figure 2-12. The propagation direction of the tidal wave along the Holland Coast is northward.

Tidal currents are generally oriented parallel to the coastline. North easterly flood currents dominate slightly over south westerly ebb currents, resulting in a north easterly residual current along the Holland Coast. This residual current has an average velocity of about 0.05 m/s and maximum surface flow velocities from 0.60 to 1.00 m/s (Wiersma and Van Alphen, 1988). Van Rijn (1997b) calculated a residual velocity of 0.1 m/s based on the difference in water depth during rising tide and falling tide.
Wind climate

Wind generates ocean waves, so prevailing winds influence the magnitude and direction of waves. In the Netherlands, the strongest winds are generally from the west, according to the zonal wind system and the latitude (50 degrees) of the Netherlands (Bosboom and Stive, 2010). The difference in warming of oceans and continents in winter and summer leads to a strong seasonality of the wind. Strong winds in the Netherlands therefore only occur during the winter period.

Wave climate

The wind climate results in a storm wave environment. The storm wave environment is characterised by Short (2005) with among others the following characteristics:

- Steep, short-crested irregular and multi-directional waves
- Deep water wave heights of 2-3 m (90% of the time) to 5-6 m (10% of the time)
- Wave periods of 5 s, longer during storms
- Directed from the west to south-west in the Northern Hemisphere
- Mainly present in the winter in the Northern Hemisphere

Apart from storm waves also swell waves are present along the Holland coast. These swell waves originate from storms in the Northern North sea, and thus are directed from the North. Some characteristics of swell waves (after Short (2005)):
• Uniform waves in direction, shape and size
• Deep water wave heights are moderate to high: 1-2 m
• Wave periods of 10s

The average breaking height along the Dutch coast ranges from 1.0 m in the summer to 1.7 m in the winter (Janssen, 2005).

Classification of the Holland Coast

The Holland coast can be characterised based on a few parameters used for the classification of coasts. Dean’s parameter, the relative tidal range and the rate of exposure are presented here for the Holland Coast.

Dean’s parameter

Wright and Short (1984) proposed to use Dean’s parameter (Eq. 2-23) a method to predict the morphodynamic state of sandy beaches based on the breaking height of waves, the settling velocity of sediment and the wave period. Dean’s parameter is sometimes called the dimensionless fall velocity.

\[ \Omega = \frac{H_b}{w_s T_p} \]  

\( \Omega \) = Dean’s parameter [-]  
\( H_b \) = Wave breaking height [m]  
\( w_s \) = Fall velocity [m/s]  
\( T_p \) = Wave peak period [s]

A value of Dean’s parameter between 1 and 6 indicates an intermediate beach, characterized by bar and rip morphology. Within this class four different intermediate beach states are defined, with increasing \( \Omega \): low tide terrace (LIT), transverse bar and rip (TBR), rhythmic bar and beach (RBB) and longshore bar trough (LBT). A value of \( \Omega \) larger than 6 points to a dissipative beach. On dissipative beaches the wave energy level is usually high, sediments are fine and the surfzone is wide. Subdued bar morphology may be present but rips are usually absent (Masselink and Short, 1993). Along the Holland Coast beaches have a parameter of 6.6 according to Janssen (2005). This value is close to the transition point of intermediate to dissipative beaches at \( \Omega = 6 \) so the Holland Coast will show characteristics of both the dissipative beach state and the longshore bar trough intermediate beach state.

Relative tidal range

The Relative tidal range (in short RTR) is introduced in Masselink and Short (1993) as the ratio of tidal range to breaker height, see Equation 2-24. Large values of RTR express tide-dominance and small values express wave-dominance.

\[ RTR = \frac{TR}{H_b} \]  

(2-24)
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\[
\begin{align*}
RTR & = \text{Relative tidal range} [-] \\
TR & = \text{Tidal range} [m] \\
H_b & = \text{Wave breaking height} [m]
\end{align*}
\]

According to Janssen (2005) the RTR along the Holland coast is 1.27, expressing a wave-dominated coast. Masselink and Short (1993) would then classify the Holland coast (with \( \omega = 6.6 \) and \( RTR = 1.27 \)) as a barred dissipative coast. See Figure 2-13.

Rate of exposure
The rate of exposure of a coast is based on a rating system of McLachlan and Brown (1990) who developed a 20 point scale on the basis of wave action, length of the surfzone, percentage of very fine sand, grain size, slope, depth of the anaerobic layer, and the presence or absence of stable burrows of benthic animals. The Holland coast scores between 11 and 12 on this scale, according to Janssen (2005), and can be regarded as a moderately exposed coast.

2-3-2 Sediment transport along the Holland Coast

Roelvink and Stive (1989) set up a model based on the terms mentioned in Section 2-2-2 on the longshore transport and calibrated the model for the Holland Coast. This resulted in net transport vectors along the Holland Coast (Figure 2-14). At approximately 1 kilometre offshore the transport vectors are oriented parallel to the shore in a North East (at Scheveningen) to North North Easterly direction. These transport vectors parallel to the coast are based on tide-dominated transport. Further nearshore this tide-dominated transport changes in wave-dominated transport, because of the increased wave-induced streaming (LH-streaming) and short wave asymmetry. Thus the onshore directed transport increases
in shallower water. The longshore component of the current also becomes wave-dominated, reduces and is more shoreward directed.

![Figure 2-14: Net transport vectors along the Dutch coast (Roelvink and Stive, 1990)](image)

**Transport rates**

Some key figures of the general sediment transport along the Holland coast are presented to give an idea of the sediment transport in this area. Wijnberg (1996) sums up different studies all concluding that in a time scale of decades the shoreline north of Egmond and south of Scheveningen is retreating and in between the shoreline is slightly prograding (e.g. Van Straaten, 1965; Kohsiek, 1984). Roelvink and Stive (1989) ascribe these longshore transport gradients to the difference in coastline angle, causing differences in the wave-driven longshore transport.

According to Wiersma and Van Alphen (1988) a sediment volume of 8 to 20 ×10⁶ m³ is
annually transported into the Wadden Sea. Van Rijn (1997b) draws the following conclusions on sediment transport rates along the Holland Coast based on morphological data (Jarkus-data) and gradients of the yearly-averaged longshore and cross-shore transport rates:

In cross-shore direction: (volumes including pores)
- 20 m water depth: 0-15 m³/m/year (+- 10) in onshore direction
- 8 m water depth: 0 m³/m/year (+- 10)

In longshore direction: (volumes including pores)
- 20 m water depth: 25-75 m³/m/year (+-15 to 30) in northward direction
- 8 m water depth: 65-150 m³/m/year (+- 40 to 60) in northward direction

Erosion volumes: (volumes for total area between Den Helder and Hoek van Holland)
- beach and surfzone (3 to -8 m NAP): 730.000 m³/year, including the nourishment volume of 440.000 m³/year
- middle shoreface zone (-8 to -12 m NAP) 750.000 m³/year

The volume of sediment crossing the -8 m NAP depth contour (from Den Helder to Hoek van Holland) in onshore direction is estimated to be about 500.000 m³/year (including pores).

2-3-3 Sediment characteristics along the Holland Coast

The average sediment characteristics along the Holland coast are discussed. The average parameters presented are based on writings in literature about results of measurements of the sediment composition along the Holland Coast. The resulting values show a large variation in both time and space between the different sources. Goal of this part of the literature research is to get a feeling of the natural variation of the grain sizes.

Average sediment size and grading

The Holland coast is characterised by sandy beaches, with non-uniform sediment, gradual transitions in sediment characteristics along the beaches and a shallow foreshore (Tonnon and Baptist, 2011).

Eisma (1968) sampled sediment along transects of the Holland coast using a Van Veen grab sampler, sampling the top 5 cm of the sediment on the sea bottom. Eisma found spatial distribution of three types of sea sands he calls type D, E and F. Type D is rather fine grained with a coarse admixture. Type E is coarser than D. Type F is much finer than type D. In the area of the Sand Motor type E is present near the coast and offshore, but a band of type F material is present parallel to the shore (see Figure 2-15). There is a band of finer sands parallel to the coastline at a water depth of 10 m to 13 m and deeper than 15 m the sediment is coarser again.

Van de Meene (1994) also researched the sediment grain sizes along the Holland coast, and he observed a jump in grain sizes from the lower shoreface to the inner shelf. The lower shoreface has median grain sizes of 150-200 µm. This changes in coarser grains in seaward direction, with median grain sizes of 300 µm at a depth of 13-14 m.
Figure 2-15: Spatial distribution of different types of sediment along the Dutch Coast (Eisma, 1968)
Spatial variations in sediment size and grading

The sediment characteristics of the Holland Coast are not easily described by average values as appeared from the large range of values from the previous section. The spatial variation of grain sizes are described (1) along the total of the Dutch Coast, (2) along the Holland Coast and (3) within a cross-shore profile in the Holland Coast.

The sediment along the shoreline of the Holland Coast is coarser compared to sediment along the shorelines of the Wadden Sea and the South West delta. Janssen (2005) concluded this with a measurement campaign at nine locations along the Dutch coast, taking 10 samples per location. The average median grain size found at the Holland Coast is $313 \, \text{µm}$, compared to an average median grain size of $224 \, \text{µm}$ for the Wadden Sea, and $218 \, \text{µm}$ for Goeree, the only measurement location to represent the South West delta area.

Within the Holland Coast the grain size seems to be larger in the South part of the Holland coast: the median grain size measured at Katwijk is $359 \, \text{µm}$, compared to a median grain size of $305 \, \text{µm}$ at Egmond. Eisma (1968) found a median diameter varying from 120 to 300 $\mu$m at the transect of Hook of Holland (to a depth of 11 m). At the transect of Scheveningen the median diameter varied between 300 and 450 $\mu$m.

Within the cross-shore profile the median grain size reduces with larger water depth according to the results of a measurement campaign performed by Wijsman and Verduin (2011) in the autumn of 2010, see Figure 2-16. Apart from this general trend variations in grain size within the surfzone of the Holland Coast are linked to bar morphology by Janssen (2005). Janssen and Mulder performed measurements along transects at Egmond and Castricum, using a Van Veen grab sampler. There are 2 bars along the coast of Egmond, with a through in between at approximately -5 m NAP. The bar morphology influences the grain size parameters as they found the sediment in the trough to be coarse with an average of $510 \, \text{µm}$, compared to the average of the total of $320 \, \text{µm}$. The grain size nearshore of the first bar (200 meters from the low waterline) varies from 246 to $377 \, \text{µm}$ and is well sorted. The grain size offshore of the second bar (400 meters from the low waterline) varies from 170 to $252 \, \text{µm}$, so is smaller than the sediment nearshore, and is poorly sorted.
Figure 2-16: Median grain size diameter (y-axis) as function of water depth (x-axis), for Reference, Sand Motor and Influence areas respectively (source: Wijsman and Verduin (2011))
2-4 Nourishment

This section is about the design and the general behaviour of nourishments. The goal of this section is to understand the impact of a nourishment on the sediment transport processes.

2-4-1 Reasons to apply a nourishment

An artificial supply of sediment on a beach or shoreface is called a nourishment. A nourishment is performed to compensate for erosion processes. The supplied sediment replaces the eroded sediment temporarily, it is no structural solution that stops the erosion process. Nourishments are therefore called ‘soft’ measures. A ‘hard’ measure against erosion is to construct a hydraulic structure structure (e.g. groin, seawall) to prevent local erosion. Besides these two general solution directions, doing nothing to prevent the erosion can also be a management strategy. The most common reasons to choose for a ‘soft’ coastal management strategy and to apply a nourishment are:

- The natural value of the area is preserved, and with this usually the recreational value as well
- A nourishment is cost-efficient
- The application of a nourishment is a foolproof method

There are various reasons to apply a nourishment (or other structure) and the most important one is to maintain or enhance the safety of the hinterland. A nourishment increases the resilience of the dunes against storm induced erosion. Furthermore, it protects the beach and dune area and properties built rather close to the edge of the dunes against storm erosion. Positive important side effects of the application of a nourishment are the maintenance or creation of a (broad) beach or even the creation or reclamation of larger areas.

2-4-2 Construction of a nourishment

The sediment used for nourishments is dredged offshore, at least a distance of 20 km from the shoreline. The sediment is usually dredged as close as possible to the location where the nourishment is made, with regard to transportation costs. The sediment size and grading of a nourishment depend on the offshore conditions at the dredging location of the source, the grain size of the sediment can best be the same size or slightly coarser than the native material, as Dean (2002) showed in his analysis of the equilibrium beach profile.

The percentage of fine material as silt and clay in the nourishment material must be small, because when the material is exposed to wave action these small grains will be placed into suspension and lost to the littoral system (Dean, 2002). The silt and clay fractions can have impact on the ecological system as they are not naturally present in the energetic nearshore region.

2-4-3 Influence of sediment composition of a nourishment on the sediment transport

The processes influencing sediment transport of nourished sediment are the same processes that transport the native sediment. Though some interesting remarks can be made on the
redistribution of sediment of nourishments and the influence of the grain size of the nourished material compared to the natural sediment.

Cross-shore sediment transport at a nourishment

Based on the grain size of the nourished material compared to the grain size of the native material the behaviour of the nourishment in the cross-shore direction can be predicted with the use of the theory of the equilibrium beach profile (Bruun, 1954). This is illustrated in Figure 2-17 and explained below.

- Coarser sediment used for the nourishment
  The equilibrium slope of the nourishment is steeper than the natural equilibrium slope, so the nourishment does not have to extend to the closure depth, as it intersects with the natural slope before this depth.

- Sediment with equal grain size used for the nourishment
  The equilibrium slope of the nourishment is the same as of the natural profile, so the nourishment has to extend to the closure depth.

- Finer sediment used for the nourishment
  The equilibrium slope of the nourishment is more gradual than the natural slope, moving nourished material offshore to the closure depth.

In reality the sediment of a nourishment will not consist of grains that all have the same size, so there probably are sediment fractions of the nourishment that are smaller and sediment fractions that are larger than the median grain size of the native sediment. The coarser fractions of the nourished sediment will thus move nearshore on a steeper part of the slope and the finer fractions of the nourished sediment will move offshore towards the closure depth. The theory of the equilibrium profile thus in theory results in sediment sorting in the cross-shore profile.
Figure 2-17: Nourishment profiles based on grain size of nourished material. Af is fill material, An is native material. (Dean, 2002)
Longshore sediment transport at a nourishment

Based on the grain size of the nourishment and the native material, differences in sediment transport quantity will cause gradients in the sediment transport longshore. The sediment size influences the coefficient $K$ in the CERC formula. $K$ is greater for finer than for coarser sediments (see Figure 2-18) and a larger value for $K$ means more longshore transport. Finer material is thus more easily transported in alongshore direction.

![Figure 2-18: Relationship of sediment transport coefficient with median grain diameter, $D_{50}$. (del Valle et al., 1993)](image)

- Coarser sediment used for the nourishment
  There is a smaller sediment transport gradient at the nourishment location than outside, leading to an updrift migration of the centroid of the nourishment. This is illustrated in Figure 2-19.

- Sediment with equal grain size used for the nourishment
  There is no sediment transport gradient caused by differences in grain size.

- Finer sediment used for the nourishment
  The shorelines updrift and downdrift of the nourishment location both accrete, with a greater accretion occurring on the downdrift side, leading to a downdrift migration of the centroid of the nourishment (Dean, 2002).
Other aspects influencing the sediment transport

A large scale nourishment can influence the sediment transport also in ways not based on the grain size of the nourished sediment.

The orientation of the coastline is changed by the large scale nourishment of the Sand Motor. The ‘bulge’ of the Sand Motor has a different orientation to waves, and thus induces gradients in longshore direction. These gradients have the effect to flatten out the ‘bulge’ to return to the equilibrium straight coastline, if the angle of incidence of the waves is not too close to the orientation of the shoreline. Furthermore, the shape of the nourishment may induce focussing of the waves at the most seaward side of the Sand Motor, which may result in additional local stirring of the sediment.

The large ‘bulge’-like shape of the Sand Motor protruding into the North Sea influences the direction and velocity of the alongshore currents, directed parallel to the coast in the situation before the construction of the Sand Motor. A decrease in flow cross section leads to an increase in flow velocity, based on the continuity principle. The flow velocity in alongshore direction will thus be larger at the Sand Motor because of the Sand Motor. The simulated currents around the Sand Motor are presented in Section 3-4. These larger currents increase the longshore directed sediment transport rate at the Sand Motor.

2-4-4 Measured sediment sorting at a shoreface nourishment at Terschelling

A research into sediment sorting at a nourishment with the use of field measurements was performed by Guillen and Hoekstra in 1996. Guillen and Hoekstra (1996) researched the grain size evolution related to a shoreface nourishment at the coast of Terschelling (The Netherlands). The results and analysis of their study is used in this thesis to give an impression of sediment sorting of a nourishment.
The nourishment Guillen and Hoekstra researched is a shoreface nourishment, a filled up trough between the middle and outer bars (500-900 m from the shoreline) with sediment with a median grain size of 25 µm coarser than the native sediment. To measure the sediment distribution Guillen and Hoekstra used a Van Veen grab sampler to take surface samples (upper 3-5 cm) in the nearshore zone, both before and after placement of the nourishment. The grain sample analysis on the samples was carried out with a settling tube. Guillen and Hoekstra made use of the concept of ‘master samples’ to decrease the variability of the grain size measurements. They constructed these master samples by taking the average of the weight percentages of each grain size fraction of all the samples in the active profile (200-1200 m from the shoreline) or in each survey.

Directly after placement of the nourishment the sediment in the area of the nourishment was observed to become coarser (17-57 µm). The most important grain size changes are noted between the shoreline and 300 m seaward, and in the offshore part of the profile, between 900 and 1200 m from the shoreline. In these zones the sediment has become finer by 5-25 µm compared to the situation before the nourishment.

Guillen and Hoekstra defined 3 zones in the cross-shore direction with a different relationship between sediment distribution and morphology. The location of these zones is consistent with a zonation on the shoreface based on hydrodynamic, i.e. basically wave-driven, processes.

- The shallowest zone, from shoreline to seaward side of offshore bar (6 m water depth). In this area are the steepest slopes and the highest sediment fining gradient (10 µm per 100 m).
- The intermediate zone, from seaward side of offshore bar (6 m water depth) to 10 m water depth. The slope of the profile is gentle and the sediment grain size is nearly constant in this zone.
- The deepest zone, extending offshore from 10 m water depth. The profile slope changes and the sediment size coarsens in offshore direction.

Guillen and Hoekstra (1996) noted that the changes in sediment size due to the nourishment are easier to recognize in the offshore part of the profile than near the shoreline, because of the cross-shore dependency of sediment variability. For instance, the changes in sediment size in the nourished zone cannot be ascribed to the nourishment because the natural variability in this area is higher than the variability caused by the nourishment.

The nourishment had a short-term and very local impact on the sediment distribution, because the former grain size distribution was re-established in a few months. Guillen and Hoekstra (1996) observed that the nourished sediment was quickly dispersed and mixed with the original deposits, and concluded that the volume of the nourished sediment was only a small part of the volume of sediment involved in the dynamics of the littoral zone.
Chapter 3

Sand Motor site description

3-1 Introduction

The Sand Motor is used as case study in this master thesis. This chapter gives more information on the design and the design goals of the Sand Motor as well as the developments in the bathymetry and the hydrodynamic conditions and sediment transport rates at the Sand Motor.

The Sand Motor is a large scale nourishment along the South Holland coast at Ter Heijde. Wind, waves and currents will transport the sand along the coast, letting the nature do the work. Projects with this line of thought are bundled under the name ‘Building with Nature’. The transport of the Sand Motor sediment will lead to a changing shape of the Sand Motor over the years and eventually the Sand Motor will be disappeared and the coast will be broader and safer. This process is visualised in computed morphological behaviour of the Sand Motor in the first 15 years in Figure 3-1.
Figure 3-1: Computed morphologic development of the Sand Motor for 0,5,10 and 15 years (Mulder and Tonnon, 2011)

3-2 Sand Motor Design

The Sand Motor consisted of 21.5 million cubic metres of sand just after construction, spread out over 128 hectares. The Sand Motor was constructed between March 2011 and November 2011 by supplying the sediment both with pipes and by rainbowing from the large scale dredging equipment of Boskalis and Van Oord. The sediment used for the construction is dredged from locations at least 20 km offshore. The sediment characteristics of the Sand Motor are described in Section 4-4-2. The Sand Motor has a hook shape in the Northern direction of the coast, this was the best alternative based on the design goals (Fiselier, 2010).
3-3 Bathymetric data of the Sand Motor

The bathymetric data used in this research consists of JARKUS data and data from Shore. JARKUS data consists of transects with data every 250 metres with 1 data set per year. Shore measures more frequently and in a finer grid, with a first data set in August 2011, after the construction of the Sand Motor. For the bathymetry at the time of the T0 measurement thus only JARKUS data was used. For the bathymetry during the other campaigns data of Shore was used as the starting point and JARKUS data was used to fill in the gaps.

The measurement area of the bathymetry relevant for this research is depicted in Figure 3-4. The red lines depict the (fine) JARKUS grid, the measurement transects with information both by JARKUS and by Shore. The green and yellow lines are transects where Shore measures. The green lines are transects between -6 m NAP and the dune foot. The yellow lines are transects oriented parallel to the shore.

Both the JARKUS and Shore data sets consist of bathymetry data measured with a sounding device in combination with a device to measure the position in the field: GPS.

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Shore measures the water depth with equipment underneath a jetski, using a Single Beam Echo Sounder with a frequency of 10 Hz. The velocity of sound in water is measured using a CTD. The velocity of sound is necessary to determine the water depth from the measurements of the Echo Sounder (De Zeeuw et al., 2013).

### 3-4 Hydrodynamic conditions at the Sand Motor

The wind climate and the subsequent wave conditions at the location of the Sand Motor are of importance as they induce the sediment transport described in Section 3-5. The current pattern around the Sand Motor due to tidal currents is described based on a previous model study.

The wind climate at the Delfland coast can be deducted from the wind measurements at the nearest survey stations: the Europlatform and Noordwijk. The frequency of occurrence of each wind direction and wind speed at these stations between 1979 and 2001 is presented in Figure 3-5. The wind roses at the survey stations of Noordwijk and the Europlatform are approximately the same. The wind at the Delfland coast originates from the South West for 40% of the time (Pekkeriet, 2011). Higher wind speeds, of 15 m/s or higher, originate mostly from South West to West direction.

![Figure 3-5: Wind roses of stations Europlatform (eur) and Noordwijk (mpn), based on time series between 1979-2001 (Tonnon et al., 2009)](image)

The wave climate along the Delfland coast can be deducted from measurements at the nearest survey stations: the Europlatform and Noordwijk. The station at Noordwijk is located at 18 m water depth and the Europlatform station at 32 m water depth. Wave data is collected once every three hours and consists of wave height and propagation direction (Pekkeriet, 2011).

The frequency of occurrence of wave height and propagation direction is presented in Figure 3-6. The wave roses clearly show a dominance of waves coming from a southwest or northern direction. The waves originating from the southwest are the storm waves, the waves originating from the north are the swell waves. The difference between the wave roses is mainly caused by the difference in water depth at the location of the survey stations. The smaller water depth causes the waves to be more refracted, the wave propagation turning more perpendicular towards the coastline.

In the T0-report on the monitoring and evaluation of the Sand Motor of Tonnon and Baptist (2011) the average wave climate on the location of the Sand Motor is calculated using a wave
transformation matrix to transform offshore measured wave conditions to wave conditions near shore. The average near shore wave climate along the Delfland coast has waves with an average wave height of 0.97 m and a wave period of 5.6 s, the extreme wave height is 5 m. The waves originate from the directions between North West West to North, but refract towards the coast to the directions between West to Northwest.

The flow of the alongshore tidal current is contracted at the location of the Sand Motor, leading to higher velocities of on average 0.9 m/s with rising tide, and up to 1.1 m/s near the west side of the Sand Motor if the wave-induced currents are from the southwest (Pekkeriet, 2011). The shape of the Sand Motor results in an eddy on the northeast side of the Sand Motor during rising and falling tide. The maximum current velocity in the eddy is 0.3 m/s (Pekkeriet, 2011).
3-5 Sediment transport patterns at the Sand Motor

According to the research of Pekkeriet (2011) the net sediment transport around the Sand Motor is directed towards the northeast. The residual northward tidal current and the wave conditions directed mainly from the southwest contribute to this transport direction.

At the southwest side of the Sand Motor the coast accretes due to the blockage effect of the Sand Motor, comparable to the sediment transport blockage of a breakwater for example. At the northeast side of the Sand Motor the coast also accretes, in this case due to the lee-side effect of the Sand Motor because the Sand Motor shields this part of the coast for high energy waves. This situation is not comparable to the lee-side of a breakwater because a breakwater stops (almost) all sediment transport along the coast, leading to lee-side erosion. In this case the Sand Motor supplies sediment to the system so there is no shortage of sediment on the lee-side of the Sand Motor.

These sediment transport rates lead to a cumulative sedimentation erosion pattern after two years (by approximation in February 2013) presented in Figure 3-9, as modelled by Pekkeriet (2011).

![Figure 3-8: Average annual sediment transport volumes (x 1000m3) near the Sand Motor, in between the +3m to -8m and -8m to -12m NAP depth contours, averaged over five years (Pekkeriet, 2011)](image1)

![Figure 3-9: Calculated cumulative erosion and sedimentation of the Sand Motor in the second year after construction (Pekkeriet, 2011)](image2)
Chapter 4

Field data on sediment composition in the Sand Motor area

4-1 Introduction

Field data of the sediment composition in the area of the Sand Motor is used to analyse the sediment sorting at the Sand Motor. The field data consists of analysed sediment samples in the area of the Sand Motor both before and after the construction of the Sand Motor. An evaluation of the results of the different measurement campaigns leads to an answer to the question how the spatial distribution of grain sizes at the Sand Motor has changed since the construction of the Sand Motor.

The different measurement campaigns are first introduced and the used measurement methods are explained (Sections 4-2 and 4-3). Subsequently in Section 4-4 the results of these measurement campaigns are presented per measurement campaign focussing on the spatial distribution of the grain size parameters in the longshore and cross-shore direction. The average sediment composition in the Sand Motor area before and after the construction of the Sand Motor is compared as well as the development of the spatial distribution of the grain size parameters in time (Section 4-5). Section 4-6 discusses the uncertainties in the use of the mentioned measurement methods and the use of measurements as such to analyse the sediment composition. Finally, the most important conclusions based on the field data are presented (Section 4-7) and hypotheses are formulated explaining the processes behind the sediment sorting at the Sand Motor (Section 4-8).

4-2 Measurement campaigns

The different measurement campaigns all have the Sand Motor and the developments at and around the Sand Motor as a focus point of the research. Still the measurement area and the exact measurement locations differ as well as the method with which the measurements are performed. The set-up of the different measurement campaigns is described in this section.
4-2-1 T0 campaign - October 2010

In October 2010 IMARES performed a measurement campaign to describe the baseline situation before the construction of the Sand Engine. IMARES focuses on the macrozoobenthos in the intertidal area and the subtidal coastal sea (Wijsman and Verduin, 2011), and a sediment analysis is part of this study.

Measurement area
The measurement locations of the T0 campaign are positioned in 12 transects perpendicular to the coast, see Figure 4-1. The measurement area stretches from south of Ter Heijde to north of Kijkduin. The measurement area interesting for this research are the transects 5 to 10, as this area matches the measurement area of the T3 campaign. Sediment samples are not taken at every displayed measurement location, as sediment analysis is not the main focus of the study (Figure 4-2).

The distance between the transects is 800 meter in the area where the Sand Motor will be located (transects 5 to 8) and 1000 meter in the areas south and north of the Sand Motor. In the cross-shore direction the location of the measurement locations is determined based on the depth. The difference in water depth between two consecutive measurement locations in the near shore zone varies between 0.5 and 2.0 meter.

4-2-2 T1 campaign - April-November 2011

Between April 2011 and November 2011 the Sand Motor was constructed with dredged sediment. The sediment was analysed for every 500,000 m³, because the sediment had to fulfill some design requirements, among others the requirement that the median grain size of the sediment of the Sand Motor has to be between 200 and 300 μm. The sediment composition
of these measurements is considered to be representative for the sediment used to construct the Sand Motor.

The samples of the T1 campaign consist of sediment samples taken from dredging barges. The location where the sediment samples were taken is not important, because this does not tell anything about the sediment distribution in the area of the Sand Motor. The dumping locations of the analysed sediment of the dredging barges are known and could be used to study spatial variations in the sediment at the initial situation. However, one of the starting points of the research is the assumption that the Sand Motor sediment is uniformly distributed, therefore the potential spatial spreading of the grain size parameters of the sediment samples is not looked into. Relevant locations for the sediment transport (trough water) are selected based on the criterium that the dumping location has to be situated at a height lower than 3m +NAP, this leaves 25 samples for analysis.

4-2-3 T2 campaign - August 2012

Imares performed a measurement campaign in August 2012 as a follow-up on the base line measurement campaign of August 2010 before the construction of the Sand Motor. The planned measurement locations of the T2 measurement campaign are the same as the locations of the T0 campaign by Imares, as this campaign in August 2012 is conducted by Imares as well (see Figure 4-1 in Section 4-2-1). However the locations where sediment is sampled differs from the T0 campaign, as locations near the former shoreline are now located on the Sand Motor and because more sediment samples are taken to analyse the now probably more dynamic sediment composition in the area. The sampling locations of the T2 campaign are shown in Figure 4-3.
4-2-4  T3 campaign - February 2013

A field measurement campaign was carried out by the TU Delft to gather field data on the current sediment distribution around the Sand Motor. The goal of the measurement campaign was to get an impression of the spatial variations in sediment size and grading around the Sand Motor. The samples were taken using a Van Veen grab sampler deployed from a boat. After procuring the sediment samples, sieve analysis was performed on these samples in the Geo Lab of the TU Delft to obtain the grain size parameters. These measurement methods are described in Section 4-3.

Measurement area
The measurement locations of the measurement campaign in February 2013 are positioned in 6 transects perpendicular to the shore, located at the Sand Motor and north of the Sand Motor. The most Northern transect (transect A) is placed in line with the NH Hotel in Kijkduin (where Argus cameras are placed), see Figure 4-4. In the cross-shore direction 11 measurement points are positioned between the 0m NAP and -11m NAP depth lines. The points are more closely spaced near interesting features (e.g. bars, gullies) and near shore, as these areas are probably the most dynamic thus more spatial resolution is useful.
4-3 Measurement methods

There are several methods to perform grain size analysis and the results of the different campaigns are not based on the same method.

For the previously described measurement campaigns the following methods were used:

- Sampling sediment with a Van Veen grab sampler
- Analysing sediment samples for grain size analysis
  - Laser diffraction technique
  - Sieving analysis
  - Removal of carbonate content from samples

4-3-1 Taking sediment samples with a Van Veen grab sampler

The Van Veen grab sampler is a low-tech device to sample sediment. The sampling of sediment in all measurement campaigns is done with the use of a Van Veen grab sampler. In this section the deployment method of the Van Veen grab sampler and the characteristic dimensions of the used grab samplers in the different measurement campaigns are presented.
The buckets of the Van Veen grab sampler are spread open using a lever and are locked in this position when letting the instrument down in the water. The lever unlocks when the Van Veen grab sampler hits the ground. When the Van Veen grab sampler is pulled upward, the buckets close and take a sample from the sea bottom. This process is illustrated in Figure 4-5. An extensive description of the sampling process used in the February 2013 campaign is presented in Appendix A-1.

![Figure 4-5: Van Veen grab sampler taking a sediment sample](source)

The Imares T0 and T2 measurement campaign made use of a weighted Van Veen grab sampler, taking a sample of about 0.1 m$^2$ of the surface. The Van Veen grab sampler used in the T3 campaign had a maximum content of approximately 2.5 liters. The Van Veen grab sampler is made of stainless steel and has a weight of approximately 5-10 kilograms. The use of this Van Veen grab sampler resulted in sediment samples of approximately the top 5 cm of the bed.

A different Van Veen grab sampler was used to sample the first measurement points in the T3 campaign (A11 and A10). The Van Veen grab sampler used for these first points was lighter and did not perform as well as the heavier one used in the continuation of the sampling. The heavier Van Veen grab sampler digs deeper into the bottom and thus results in more usable samples with a minimum sampling volume. The way of lifting the Van Veen grab sampler was altered and improved by the lifters during the days and different persons have lifted the Van Veen grab sampler. The way of lifting the grab sampler could influence the depth of the sample grabbed by the grab sampler in the bottom layer.

### 4-3-2 Analysing sediment samples for grain size analysis

Sediment samples can be analysed with different techniques. The laser diffraction technique with which the grain size parameters of the data of the Imares campaigns were obtained is
described in short. The sieving technique performed on the February 2013 samples and the preparatory procedure of removing shell fragments are described in more detail. The following methods were used and are described:

- Laser diffraction technique
- Sieving analysis
- Removal of carbonate content from samples

The sediment samples of the T0 and T2 campaigns were analysed by a Malvern particle sizer, based on laser diffraction technique. The diffraction pattern of the light of a laser beam gives information on the grain size distribution of a sample. The samples were analysed by the laboratory of NIOO-CEME. These sediment samples were not pre-treated before the measurement.

The sediment samples taken from the dredging barges at T1 were analysed by Boskalis Dolman bv, laboratory for Environmental and Geo technical research. The laboratory sieved the samples according to the sieving procedure mentioned in BS 1377 (British Standard). The sediment samples of the February 2013 measurement were also analysed with the sieving procedure according to the British Standard. The sieving of these samples was performed in the Geo laboratory of TU Delft. Either the dry or the wet sieving method was applied, depending on the expected amount of fine material in the sample. A description of these sieving methods can be found in Appendix A-3.

The removal of shell fragments is a preparatory procedure, which is generally applied before sieving the sample. This process was, however only applied to a few representative samples of the February 2013 campaign. Consequently, some interpretation is needed to analyse the sieve results, as the sediment samples were taken in areas were shell fragments can be expected. Large shells and fragments were removed by the sieve with the largest apertures (the 1.18 mm sieve), though shell fragments were observed visually in lower sieves as well. The method used to remove small shell fragments from a sediment sample is described in Appendix A-2.

4-4 Results of measurement campaigns

4-4-1 Results T0 campaign - October 2010

The results from the Imares measurement campaign are recorded as median grain diameter and weight percentages of the amount of silt (<63 µm), very fine sand (62.5–25 µm), fine sand (125–250 µm), medium sand (250–500 µm) and coarse sand (500–1000 µm).

Average value analysis

The average values are based on 31 samples taken at 31 sample locations. The median grain size of the sediment samples has an average value of 242 µm and a standard deviation of 52 µm.
Spatial distribution of grain size parameters

The values of the grain size vary in space. An overview of the spatial variation of the grain size parameters is presented in Figure 4-6.

In general the grain sizes are largest nearest to the shore and decrease in offshore direction, this is in agreement with theory (Medina et al., 1994; Guillen and Hoekstra, 1997). The largest grain sizes overall are found in transects 7 and 8 at the locations nearest to the shoreline. Points 8.4, 9.5 and 10.5 show a remarkably larger grain size than their surrounding points. This would not have been expected based on the mentioned theory of decreasing grain size in offshore direction, but many studies have shown that sediment gradations can vary considerably in space.

The spatial distribution is looked upon in a quantitative manner in the following sections, focussing on the alongshore variation, the general cross-shore variation and the dependency on depth and bathymetry (both also in the cross-shore direction).

Alongshore variation

The variation of the median grain size in the alongshore direction is represented by the deviation percentages of the master sample of the transects from the average of the total measurement area.

A master sample is created per transect by adding all grain samples taken from over the profile (Medina et al., 1994). The measurement results per measurement location are multiplied by a factor according to the size of the profile area that this measurement location represents. The construction of a master sample is explained in further detail in Appendix B-2.

The most Northern transect has the largest positive deviation in median grain size, based on the master samples of the transects and the average values of the measurement area (Table 4-1). Other than this deviation the alongshore variation is small at T0.
Table 4-1: Alongshore variation of median grain size from total average - T0 (October 2010)

<table>
<thead>
<tr>
<th>Transect</th>
<th>Master sample $D_{50} \text{ [\mu m]}$</th>
<th>Deviation percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>259</td>
<td>11.10%</td>
</tr>
<tr>
<td>9</td>
<td>203</td>
<td>-13.15%</td>
</tr>
<tr>
<td>8</td>
<td>237</td>
<td>1.52%</td>
</tr>
<tr>
<td>7</td>
<td>234</td>
<td>0.27%</td>
</tr>
<tr>
<td>6</td>
<td>242</td>
<td>3.89%</td>
</tr>
<tr>
<td>5</td>
<td>225</td>
<td>-3.71%</td>
</tr>
<tr>
<td>Weighed average</td>
<td>233</td>
<td>0%</td>
</tr>
</tbody>
</table>

Cross-shore variation

The variation of the median grain size in the cross-shore direction is analysed as the relation between the grain size and the water depth. This relation is looked upon for the area as a whole and for the different transects independently to see whether there are certain trends. The relation between grain size parameters and the water depth is researched by plotting the relative median grain size and the uniformity coefficient of all measurement points against the water depth of the measurement location. From theory (Medina et al., 1994) it is expected that the grain size decreases in offshore direction, so for smaller depths larger grain sizes will be found compared to larger water depths. The T0 measurements shows this expected trend, visualized by the linear fit of the relative median grain sizes in Figure 4-7.

The relative median grain size at a measurement location is defined as the fraction of the measured median grain size over the master sample of the transect (Eq. 4-1). The definition of the master sample is explained in Appendix B-2.

$$Relative \ D_{n, point} = \frac{D_{n, point}}{D_{n, transect}}$$

(4-1)

The average offshore fining trend of the total area can be quantified by a 20 % positive deviation nearshore and 20 % negative deviation in the offshore part of the profile. Transect 7 (positioned at the centre of the Sand Motor) has the largest grain size variations in the profile, varying from a 20 % positive deviation nearshore to a negative deviation of 40 % offshore. Only transect 10 (North of where the Sand Motor is later built) deviates from the other transects with an opposite trend of relatively coarser grains offshore, though this could be caused by an outlier in the measurements as the linear fit is based on only 5 measurements an outlier would have much influence on the fit.

The uniformity coefficient of the samples sediment varies between 1.7 and 2.6, and an average value between 2 and 2.5. An outlier of 4 in transect 6 is disregarded. The uniformity coefficient does not show a clear depth dependency (Figure 4-8).

Apart from the general gradient of the grain size over the entire transects, local gradients are interesting to observe the measured sediment sorting in the cross-shore direction in more detail. Figure 4-9 shows the measured values and a visualisation of the continuous sediment grain size over the profile based on the averages of measured values per 1 meter water depth. It must be noted that the lines in the plot must be read as estimations of the sediment grain
size in the profile based on 5 or 6 measurement over a length of 10 meters. The number of measurements is too small to represent the local variations of the grain size.

However, based on this figures on the relation between the absolute median grain size and depth before the construction of the Sand Motor a few observations can be made:

- The absolute differences in median grain size per transect vary between 75 and 150 $\mu m$. These differences are larger than the differences between the master samples in the alongshore direction and the gradient in median grain size is larger as well in the cross-shore direction.

- The spread in the median grain size related to depth is about the same over the profile (about 80 $\mu m$). This is in contradiction with the expectation that the variations in grain size are the largest nearshore. The unexpectedly large spread in the measured median grain size in the deeper part of the profile could be the reason behind this.

- The transects North of the location where the Sand Motor is later build show a notable high median grain size at 10–11 m water depth. This is in contradiction with the general fining trend in the offshore direction and could be caused by sediment characteristics of that area, unrelated to the transport processes and the layer of erosion and deposition. At this water depth not much bed level change takes place, so it could well be that the ‘old’ sediment deposits are sampled and measured here.
4-4 Results of measurement campaigns

4-4-2 Results T1 campaign - April to November 2011

The results from the measurements of the T1 campaign are presented in reports of Boskalis Dolman bv, laboratory for Environmental and Geo technical research. Per measurement location the grain size parameters are given per 10% passing percentage.

The median grain size of the samples varies from 224 to 399 µm, with an average value of 278 µm and a standard deviation of 30 µm. The uniformity coefficient ranges from 1.89 to 2.29 with an average value of 2.05 and a standard deviation of 0.10.

4-4-3 Results T2 campaign - August 2012

The results from the Imares measurement campaign in August 2012 are recorded as median grain diameter and (weight) percentages of the amount of silt (<63 µm), very fine sand (62.5–25 µm), fine sand (125–250 µm), medium sand (250–500 µm) and coarse sand (500–1000 µm).

Average value analysis

The average values are based on 60 samples taken on 60 locations. The median grain size of the sediment samples has an average of 305 µm and a standard deviation of 90 µm.
Spatial distribution of grain size parameters

The values of the grain size vary in space. An overview of the spatial variation of the grain size parameters is presented in Figure 4-10. In general the larger median grain sizes are found in the areas of larger water depth. It is remarkable that the top 3 points with the largest median grain size are all in the same (most northern) transect. A quantitative analysis of the spatial variations is presented in the following sections.

![Median grain size - T2 and Uniformity coefficient - T2](image)

**Figure 4-10:** Spatial distribution of grain size parameters - T2 (August 2012). The median grain size and uniformity coefficient are shown as a circle at its measurement location, the color of circle corresponds to the left color bar with median grain size in $\mu m$. The bathymetry is based on Jarkus data, corresponding to the right color bar with water dept in m NAP.

Alongshore variation

The variation of the median grain size in the alongshore direction is represented by the deviation percentages of the master sample of the transects from the average of the total measurement area. The construction of a master sample is explained in Appendix B-2.

From Table 4-2 it is clear that in August 2012 transect 10 consists of relatively more coarse material, and transect 5 and 8 of relatively fine material. The other transects can be considered to have an average median grain size.

**Table 4-2:** Alongshore variation of median grain size from total average - T2 (August 2012)

<table>
<thead>
<tr>
<th>Transect</th>
<th>Master sample $D_{50} \ [\mu m]$</th>
<th>Deviation percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>381</td>
<td>25.87%</td>
</tr>
<tr>
<td>9</td>
<td>309</td>
<td>1.93%</td>
</tr>
<tr>
<td>8</td>
<td>247</td>
<td>-18.31%</td>
</tr>
<tr>
<td>7</td>
<td>324</td>
<td>7.12%</td>
</tr>
<tr>
<td>6</td>
<td>294</td>
<td>-2.80%</td>
</tr>
<tr>
<td>5</td>
<td>262</td>
<td>-13.46%</td>
</tr>
<tr>
<td><strong>Weighed average</strong></td>
<td><strong>303</strong></td>
<td><strong>0%</strong></td>
</tr>
</tbody>
</table>
Cross-shore variation

The relation between the grain size parameters and the water depth is used to analyse the variation of the sediment composition in the cross-shore direction. The relative dimensionless median grain size (Eq. 4-1) is plotted against the water depth at the measurement locations and linear fits are made with the use of MATLAB. The result is presented in Figure 4-11. The trend lines of the median grain size have different orientations. Three of the transects (6,7 and 9) show a clear to strong trend with larger grain sizes offshore, while the other three transects (5,8 and 10) show a weak to clear trend for smaller grain sizes offshore. The uniformity coefficient of the samples is also plotted against the depth, see Figure 4-12. There seems to be a small trend of decreasing uniformity coefficient in offshore direction.

The local gradients of the median grain size related to water depth give more information on the variation of the median grain size within the profile (Figure 4-13). From this representation of the median grain size over the water depth it is clear that a linear fit is not useful to describe the grain size variations in the cross-shore direction.

- The absolute differences in median grain size per transect vary between 150 and 225 $\mu m$. These differences are larger than differences between the master samples in the alongshore direction and the gradients are larger as well as the large variations in the cross-shore direction take place over a small part of the profile. The gradients of the mean grain size in the alongshore direction might be large as well though there is no measurement information of closely spaced points in alongshore direction sampled in the same measurement campaign.

- The spread in the median grain size related to depth varies over the profile. Near shore and in the offshore part of the profile (8–10m water depth) the variation in grain size at these depths is the largest to about 250 $\mu m$, while the spread in grain sizes has a minimum of 100 $\mu m$.

- All transects show the same general trend: coarser sediment nearshore and offshore as well, with a minimum median grain size between 3–8 m water depth. The strong
offshore coarsening trend of transect 6 in Figure 4-7 is probably caused by a lack of measurement data in shallower water, where most likely a coarser sediment would have been measured.

The local variations of the grain size within the transects are more reliable compared to the grain size-depth relation based on data of the T0 campaign, because the transects have been sampled with a higher spatial density of measurement locations. Though it must be noted that this plot of the median grain size related to the depth is not a representation of the median grain size in the cross-shore direction as the bathymetric profile is usually not a linear profile. Local morphologic features as bars and through can influence the sediment composition without appearing in the plot.

![Figure 4-13: Median grain size (absolute value) related to water depth - T2 (August 2012). The markers are the measured values, the lines connect the average values per 1m water depth.](image)

4-4-4 Results T3 campaign - February 2013

In this section the results are presented of the measurements of the T3 campaign. The average grain size parameters and the spatial distribution of these parameters is discussed first. Visual observations made during the measurements are described in the third section. In the fourth section the results of the removal of the carbonate content from some of the samples are discussed.

The data of all the samples of the weights per fraction was used by Matlab to give the grain size parameters for every sample and averages per measurement location. These data is considered as the result of the measurement campaign. An analysis of the results was carried out using Matlab to present graphs of sieve curves, relations between grain size and depth and
spatial overviews of magnitudes of grain size parameters. The average values in the alongshore and cross-shore directions can be compared quickly in the tables. Detailed information on the transformation of measurement data to grain size parameters and an analysis of the measured differences within a measurement location can be found in Appendices B-1 and C respectively.

**Average grain size parameters**

The average median grain size for all the samples of the February 2012 measurement campaign is 273 $\mu m$. The median grain size varies considerably in the area, this is reflected by a standard deviation of 71 $\mu m$ of all samples of this average. The uniformity coefficient of all samples has an average value of 1.88, with a standard deviation of 0.33.

**Spatial variation in grain size parameters**

The measurement results show a considerable variation of the grain size parameters in alongshore and cross-shore direction. A general overview of the spatial variation of the values of the median diameter and the uniformity coefficient is given in Figures 4-14. The grain size parameters median diameter and uniformity coefficient are represented by the size and color of the circles in these figures. The location of the circles matches the location of the measurement point, seen from above like a map view.

![Figure 4-14: Spatial distribution of grain size parameters - T3 (February 2013). The median grain size and uniformity coefficient are shown as a circle at its measurement location, the color of circle corresponds to the left color bar with median grain size in $\mu m$. The bathymetry is based on Jarkus data, corresponding to the right color bar with water dept in m NAP.](image)

**Alongshore variation**

The spatial variation in the alongshore direction is researched by looking into the deviation of the master samples from the average value of the median grain size of the total measurement area. In Appendix B-2 the construction of the master samples is explained.
A clear distinction can be made between the transects located at the Sand Motor (C, D and E) and the transects North of the Sand Motor (A, B and F). The transects at the Sand Motor have relatively coarser sediment and the transects North relatively finer sediment. The absolute difference between the average median diameters of these two groups is approximately 100 µm, see Table 4-3.

**Table 4-3: Alongshore variation of median grain size from total average - T3 (February 2013)**

<table>
<thead>
<tr>
<th>Transect</th>
<th>Master sample $D_{50}$ [$\mu m$]</th>
<th>Deviation percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>251</td>
<td>-6.27%</td>
</tr>
<tr>
<td>F</td>
<td>195</td>
<td>-27.17%</td>
</tr>
<tr>
<td>B</td>
<td>189</td>
<td>-29.55%</td>
</tr>
<tr>
<td>C</td>
<td>287</td>
<td>6.91%</td>
</tr>
<tr>
<td>D</td>
<td>343</td>
<td>27.89%</td>
</tr>
<tr>
<td>E</td>
<td>320</td>
<td>19.38%</td>
</tr>
<tr>
<td>Weighed average</td>
<td>268</td>
<td>0%</td>
</tr>
</tbody>
</table>

**Cross-Shore variation**

In the cross-shore direction the variation in grain size parameters is researched with the use of the relation between the grain size parameters and the water depth.

Figure 4-15 presents the relative dimensionless median grain size (Eq. 4-1) related to depth with a linear fit approximating the trend of the measured values. The spatial variation in grain size parameters in cross-shore direction is extreme directly North of the Sand Motor where the first two measurement points near shore in transects B and F have a significantly larger grain size compared to the rest of these transects. In deviation percentages this variation can be expressed as a 20 to 40% positive deviation near shore and a negative deviation of 30 to 45 % in the offshore part of the profile.

The uniformity coefficient is also plotted against the water depth per measurement location (Figure 4-16), and a distinction can be made between the transects at the Sand Motor and the transects North of the Sand Motor. For the Sand Motor transects (C,D and E) the uniformity coefficient varies between 1.5 and 2 and does not show a clear trend related to the water depth. However, for the transects North of the Sand Motor (A and F) the uniformity coefficient shows an offshore increasing trend, meaning that the sediment offshore is more graded, thus less sorted than the sediment nearshore.

Local gradients in the median grain size related to the depth are visualised in Figure 4-9 where and approximation of the variation of the grain size over depth is presented, based on averages of measured values per 1 meter water depth. Based on observation of Figure 4-9 the variation in median grain size in cross-shore direction of the transects directly North of the Sandmotor (B and F) appears to have the same pattern related to the water depth. A minimum of the median grain size is found at a water depth of 7–8m. The transects at the Sandmotor (D and E) also show a comparable distribution of the sediment in the cross-shore, with higher grain sizes and a minimum grain size located more shoreward at 4–6 m water depth.
Figure 4-17: Median grain size (absolute value) related to water depth - T3 (February 2013). The markers are the measured values, the lines connect the average values per 1m water depth.
Visual Observations

Characteristics of the samples were also achieved by visual observation of the samples in first instance, as well as during the sieving process. Some samples contained organic matter or a considerable portion of fine material. Furthermore shell fragments were found in some of the samples.

A black colour of the sediment indicates the presence of organic matter, see for example a photo of sediment sample B11-I in Figure 4-19. This was best visible (and deductible from the odour as well) after storage of the sediment samples for a few days. The measurement locations at which at least one of the samples contained organic matter are presented in the spatial plot in Figure 4-20. From this figure it is clear that there is less organic matter present in the top bottom layer at the Sand Motor (transect C and D especially).

Fine material is observed as a muddy (silty) or clayey substance, see for example the photos of 2 sediment samples with fine material in Figure 4-18 and Figure 4-19. Fine material is only observed in the transects North of the Sand Motor, not in the transects directly on the Sand Motor.

Shells and smaller shell fragments were present in some of the samples. The larger shells were removed by the largest sieve, but the part of the sample that passed the first sieve sometimes still contained shell fragments. For the transects North of the Sand Motor the presence of large amount of shell fragments was noted down and is presented in Figure 4-20.

Figure 4-18: Photo of sediment sample F10-II: fines visible

Figure 4-19: Photo of sediment sample B11-I: fines and organic matter visible
Influence of shell fragments on the sieve analysis

In the previous section the presence of shell fragments was visually observed in some of the samples. It is investigated to what extent shell fragments in the sediment influence the obtained sediment characteristics after the sieve analysis. For this purpose, the results of the sieving analysis after preparation are compared with the results at the same location without removal of the shell fragments. The difference between the two results shows the effect of the removal of shell fragments with acid. This is not only useful for the considered samples, but this knowledge can also be used for the interpretation of the results of all other samples.

The effect of the pre-treatment was similar for the treated samples. The samples taken at measurement location C05 are taken as an example here, and these results can thus be representative for the behaviour of the other pre-treated samples as well. In Figure 4-21 the sieve curves of the not pre-treated sample and the pre-treated sample are plotted. The pre-treated samples have a higher passing percentages for smaller grain sizes, resulting in a smaller median grain size. Figure 4-22 shows the difference in weight percentages per fraction.

The following results are concluded on the effect of removing the shell fragments from the sediment sample before sieving:

- The weight percentage of the larger fractions (larger than 300 \( \mu m \)) is smaller than measured with the original measurement method by about 2%. So the weight percentage of the larger fractions is somewhat overestimated with the original method, consequently the weight percentages of the smaller fractions are underestimated by the same percentage. An overestimation of the weight percentages leads to an overestimation of the grain sizes. This overestimation is the largest for the higher nominal grain diameters: the \( D_{90} \) is overestimated with almost 50 \( \mu m \), degrading to 13.5 \( \mu m \) for the \( D_{50} \), to 4.5
Figure 4-21: Sieve Curves of samples with and without shell fragments - measurement location C05. The symbol * denotes the pretreated samples, where shell fragments have been removed.

Figure 4-22: Difference in weight percentage between a pretreated and non-pretreated sample. These samples originate from the same sample (II) taken at location C05. The symbol * denotes the pretreated samples, where shell fragments have been removed.
µm for the D_{10}. This result was expected based on the visual observation of small shell fragments in the larger sieve fractions.

- The uniformity coefficient is barely influenced by the decrease in nominal diameter values. Both the D_{60} and the D_{10} are lower for the pre-treated samples, but they changed in a ratio that does not effect the sediment grading. This is also visible in 4-21 where the steepness of both sieve curves is comparable.

The knowledge that the grain size diameters following from the sediment analyses are over-estimated is not incorporated in the results just now, but is included in the interpretation of the results. This way, the origin of the measurement data stays clear.

4-5 Comparison of results of the different measurement campaigns

In this section the results of the spatial distribution of grain size parameters of the different measurement campaigns are compared. Comparison of the different sediment distributions can lead to an overview of the development of the sediment distribution of the sediment in time.

4-5-1 Average sediment composition in measurement area

The average sediment composition in the Sand Motor area has changed according to the weighed averages of the different campaigns, see Table 4-4. Though these average values do not show the variation within the measurement campaign. The sediment compositions could be statistically comparable when the standard deviations of both data sets are large and the difference between the mean values is small.

Table 4-4: Average and standard deviation of measurement campaigns

<table>
<thead>
<tr>
<th>Transect</th>
<th>T0</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighed average</td>
<td>233</td>
<td>278</td>
<td>303</td>
<td>268</td>
</tr>
<tr>
<td>[µm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>52</td>
<td>30</td>
<td>86</td>
<td>71</td>
</tr>
<tr>
<td>[µm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of measurements</td>
<td>31</td>
<td>25</td>
<td>49</td>
<td>55</td>
</tr>
</tbody>
</table>

The median grain sizes of the data sets of the campaigns at T2 and T3 are expected to be not significantly different as there is no reason for the sediment composition in this area to change, when no sediment is added or removed (manually) in this system. This expectation is supported by the probability density function of the median grain sizes of the different campaign in Figure 4-23. The data sets of T2 and T3 have large overlapping areas due to the large standard deviations. This visual observation is supported by the results of the t-test (see Appendix D-1) on these data sets. Using the t-test it was proven that datasets T2 and T3 do not differ significantly.

The same approach shows that the data set of measurements taken before the construction of the Sand Motor (T0) is significantly different than both data sets obtained after the construction of the Sand Motor (T2 and T3).
Field data on sediment composition in the Sand Motor area

The median grain size of the sediment deposited at the Sand Motor (T1) is significantly different (larger) than the sediment that was measured in the T0-campaign in this area. And the sediment from the measurement campaign after the construction of the Sand Motor (T2 and T3) is statistically considered to have the same median grain size as the sediment that was used to construct the Sand Motor. The T1 data set consists of too little samples to use the normal t-test. As the standard deviation of the median grain size of T1 is not similar to the standard deviations of the other campaigns Cochran’s t-test (Appendix D-2) was used to determine whether T1 is significantly different than the other data sets.

The above observations on the sediment composition are based on the median grain size alone, though the sediment composition can not be represented by the median grain size as the composition is not necessarily symmetrical around one peak. This is illustrated by the sediment composition of the different measurement campaigns in Figure 4-24.

Although this figure is a good illustration of the importance to take other parameters than the median grain size into account, the data in the figure is not reliable. The reliability of the original measurement data is brought down for the T0 and T2 series twice by using the linearised (on a semilog-plot) sieve curve. Once the sieve curve is used to determine the nominal grain sizes from the weight percentages, and the second time the sieve curve is used the other way round to get the weight percentages for the fractions of the British Standard. These approximations can lead to an overestimation of the larger grain sizes, so this could explain the large content of the 450–600 $\mu m$. 

Figure 4-23: Normally distributed probability density function of the median grain size of the total datasets of the different measurement campaigns. The average median grain size, the median ($\mu$) of the normal distribution, is depicted with symbol ‘o’ in the figure and the standard deviation with symbol ‘□’.
4-5 Comparison of results of the different measurement campaigns

Figure 4-24: Sediment composition of the measurement campaigns
4-5-2 Framework of transects for spatial comparison

The measurement locations of the different surveys differed. Therefore a framework is created to be able to compare the measurement locations of the different campaigns. Either the nearest transect or a weighed average of the transects from other surveys was used to derive proxies for the sediment properties on the 2013 transects.

In Figure 4-25 the locations of the measurement points are pictured in one figure with the bathymetry of the Sand Motor area measured in February 2013. Based on this figure and the distances between the different transects, the transects of the Imares campaigns are matched to the transects of the T3 campaign (see Table 4-5). Transect A, F and D found a close enough match with a single transect with a distance of under 150 m. Transect B and F are compared with the weighed composition of the results of 2 transects, the weighing factors are determined based on the distance of the surrounding transects. Transect C is positioned at the tip of the Sand Motor, a very dynamic location, and with an environment that is not comparable to the environment at transect 8. Transect 7 on the other hand is located too far away from transect C to serve as a comparison on its own. For these reasons the results of transect C can not be compared to earlier results.

Note that in the next sections the transects of the T0 and T2 campaigns will be denoted with the associated transect letters of the T3 campaign as presented in Table 4-5.

![Figure 4-25: Locations of measurement points of different measurement campaigns. Pink dots: T3 (February 2013); white dots: T2 (August 2012); dark grey dots: T0 (October 2010). The light blue circles are the measurement points of T2 that are not taken into account.](image-url)
### 4-5-3 Sediment sorting in time

Relative values and the changes in the relative distribution of the median grain size are researched as the absolute values can not be compared due to difference in the measurement method and the hydrodynamic conditions preceding the measurements. It is stressed that although the absolute values of the different campaigns are presented in this section, they can not be compared directly.

#### Alongshore variation in time

The alongshore variation in sediment parameters is expressed by comparing the master sample median grain size per transect to the average median grain size of that measurement, see Equation 4-2. This deviation is expressed as a percentage and for all transects the deviations are presented in Table 4-6.

\[
Relative \ D_n,\ transect = 1 - \frac{D_n,\ transect}{D_n,\ total}
\]  

(4-2)

<table>
<thead>
<tr>
<th>Transect</th>
<th>T0</th>
<th>T2</th>
<th>T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>259</td>
<td>381</td>
<td>251</td>
</tr>
<tr>
<td>F</td>
<td>203</td>
<td>309</td>
<td>195</td>
</tr>
<tr>
<td>B</td>
<td>228</td>
<td>263</td>
<td>189</td>
</tr>
<tr>
<td>D</td>
<td>234</td>
<td>324</td>
<td>343</td>
</tr>
<tr>
<td>E</td>
<td>238</td>
<td>286</td>
<td>320</td>
</tr>
</tbody>
</table>

**Table 4-6: Relative median grain size of transects for the different measurement campaigns**

<table>
<thead>
<tr>
<th>Transect</th>
<th>T0</th>
<th>T2</th>
<th>T3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>259</td>
<td>381</td>
<td>251</td>
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<tr>
<td>F</td>
<td>203</td>
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<td>B</td>
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<td>D</td>
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<td>343</td>
</tr>
<tr>
<td>E</td>
<td>238</td>
<td>286</td>
<td>320</td>
</tr>
</tbody>
</table>

**Weighed Average**  233  303  268
From this comparison of the development of the relative magnitude of the master samples of the different transects, the following observations are made:

- The spatial differences in median grain size for the considered transects have increased as transect F and B have become relatively more fine and transects D and E more coarse. At T0 the differences between the transects were much smaller than at T2 and at T3 even larger. The bandwidth of relative difference from the weighed average increased from 15% to 60% in 2.5 years. At T3 a clear distinction can be made between the Sand Motor transects D and E and the other transects (A,F and B). In the time period T2-T3 the Sand Motor transects (D and E) have become relatively more coarse in time and (thus) the other transects have become relatively more fine.

- The sediment at the Sand Motor location has become coarser. At the Sand Motor transects D and E the median sediment grain size has increased both relatively and absolutely. The median grain size at the Sand Motor is large compared with the other transects in February 2013, while this was not the case in October 2010, before the construction of the Sand Motor, or in August 2012, after construction of the Sand Motor. In February 2013 a deviation of the average median grain size is found at the Sand Motor of 20 to 30% while in earlier measurement campaigns no significant difference of the weighed average was found.

- The transects with relatively more fine sediment shift northward in time. At T2 the transect with the finest material in the Sand Motor area is transect B, at T3 this is the case for transects B and F. Additionally, transect A has changed from transect with the highest median grain size to a transect with a median grain size below average.

**Cross-shore variation in time**

The variation of the grain size parameters in the cross-shore direction researched per measurement campaign showed high variations in the median grain size and the inability to characterise this variation with a linear fit to the data. The smaller scale variations showed the presence of a minimum median grain size in the profile and coarser sediment near shore. The uniformity coefficient showed less variation related to the water depth and is therefore not analysed in this section.

The distribution of the grain size in the cross-shore is researched related to the water depth. The measurement area from -12m to 0m NAP is divided in 12 bins dependent on the depth. The measured grain size parameters are averaged per bin to better visualise the trend of the grain size parameters, but it must be noted that this is an approximation of the true trend and for some areas a bin width of 1 meter will not be small enough to capture small variations. However, the concentration of taken sediment samples is not high enough to make smaller bins useful.

The location of the minimum median grain size appears to shift in the offshore direction, see Figure 4-26. Before construction of the Sand Motor the minimum $D_{50}$ is located at -8m water depth, one winter later in August 2011 (T2) the minimum is measured at -4m and another winter later in February 2013 (T3) at -5.3m the minimum median grain size is found. The construction of the Sand Motor resets the natural distribution of sediment and the location of the smaller sediment fractions.
The shaded areas in the plot are 95%-confidence intervals and are based on the standard error of the mean, which depends on the standard deviation and the number of the samples per bin, see Equation 4-3.

\[
ci_{95\%} = \bar{x} \pm 1.96 \frac{\sigma}{\sqrt{n}} \tag{4-3}
\]

The different areas of the researched area behave differently. A distinction is made between the Sand Motor area and the area directly North of the Sand Motor. Transects in these areas are grouped and the average values per bin represent the cross-shore sediment distribution in these areas (Figure serie 4-27).
Field data on sediment composition in the Sand Motor area

At the Sand Motor (transects 6, 7, C, D and E)
North of the Sand Motor (transects 8, 9, B and F)

Figure 4-27: Development of the average median grain size at the Sand Motor and North of the Sand Motor related to water depth. The markers show the measured values of the measurement campaigns (▲ = T0, ■ = T2, • = T3), the lines connect the average values per 1m water depth.

4-6 Discussion

This section discusses the uncertainties in the use of (1) the different measurement methods, (2) data processing techniques and (3) the interpretation of the data.

Measurement method

Sampling of sediment samples
A number of times a sample is taken from a larger volume of sediment. The way a sample is taken could influence the representativeness of the grain size distribution of the final sample. Furthermore, the number of times sediment has to be sampled based will probably decrease the reproducibility of this part of the measurement.

1. Van Veen grab sampler, from sea bottom
   The Van Veen grab sampler is expected to be unbiased in taking a sample from the sea bottom. Though it could be argued that the Van Veen grab sampler takes a larger volume from the top layers compared to the lower sediment layers, based on the design and the way it closes. This would lead to an overestimation of the presence of top layer material.

2. Hands/small shovel, from Van Veen grab sampler
   Taking a sample from the Van Veen grab sampler is an unbiased process and the method is based on the quantity of material in the grab sampler. When little material is sampled,
all the material is scraped out of the sampler with a small shovel. When more than
enough material is sampled, a handful is taken from both sides of the grab sampler.
The presence of water in the grab sampler probably results in the loss of fine material
when the Van Veen grab sampler is opened and the water flows out, taking with it the
finer grains.

3. Spoon, from sample bag (to be put in oven)
A sample is taken from the sediment sample taken with the Van Veen grab sampler
using a spoon. Only the part of the sample that is going to be sieved is put in the oven.
As impartial as possible an estimated amount of 150 g of material is taken from the
sample. Scoops are taken from one of the corners of the bag and the centre, taking care
to scoop from top to bottom of the bag. A representative amount of larger shells is put
in the sample tray as well.

4. Spoon, from sample tray (to be sieved)
From the dried sample a selection of material is made if the oven sample is too big.
Sieving more than 150 g is not convenient because sieves can become overloaded with
sediment if the sample is poorly graded. The entire sample is but in the bowl and a part
of the sample is removed if the sample is too large. Material to be removed is scooped
from top to bottom, so a representative sample is removed and a representative sample
remains.

Reproducibility of sieve analysis
Reproducibility of the experiments is an important factor to be able to call an outcome
reliable. The standard deviation within a sample was measured to be 9 \( \mu m \) for the median
diameter (see Appendix C-3). This value is based on the comparison of two samples taken
from the same sample. This standard deviation represents the reproducibility of the sieving
analysis though it is only based on one test and comparing one type of sediment sample.
More tests also on different samples are necessary to say something about the reproducibility
of the sieving analysis.

Variation at a measurement location
In the measurement campaign of February 2013 two or more samples are analysed per meas-
urement location and the average standard deviation of the median diameter was meas-
ured to be 15 \( \mu m \). Though the standard deviation was shown to reach values of about 50
\( \mu m \) (Appendix C). The cause of the standard deviation within an area could be the spatial
variation of the grain size (the measurement surface area is a circle with a radius of 7 meters)
(or could be caused by errors in the grain size analysis.
The smaller variations are probably caused by spatial variations in the sediment composi-
tion as these are shown to be large by other field measurements (Wijsman and Verduin, 2011;
Eisma, 1968; Janssen, 2005). Larger variations can be caused by differences in sieving method
or differences in sediment characteristics like shells or organic material influencing the sieving
analysis.

Influence of sieving method on the sieve analysis
The use of a different type of sieving method has a lot of influence on the outcome of the
sieving analysis. The decision on using the wet or the dry sieving method is based on the
visual analysis of the sample. If fine material appears to be present the wet sieving method
is used, otherwise the quicker dry sieving method is used. Using the dry sieving method on a
sample when it contains a significant fraction of fine material can lead to the clogging of fine material and then leads to too high values for the grain size diameters. An example is shown in Appendix C-5 where the median diameter of two samples of the same area are treated with a different sieving method and a difference in median diameter of 91 µm is measured.

**Influence of shell fragments on the sieve analysis**

The removal of shell fragments influences the weight percentages per sieve fraction and consequently the median grain size. The set of 14 samples that was pre-treated to measure the influence of the shell fragments showed deviations in the magnitude of the influence, this can be attributed to the spatial variation of the amount shells. Not removing the shell fragments before sieving thus influences the outcome of the grain size analysis of different locations differently and thus also affects the computation of the spatial differences.

**Data processing**

**Processing of weight percentages to nominal grain sizes**

The nominal grain sizes are determined based on a sieve curve graph of the grain size related to the passing percentage. This sieve curve plot approximates the area between the data points to be linear connected (on a semilog-scale plot) although in theory and practice the sieve curve looks more like an s-shape, without angles. Trying to mimic the shape of the curve with a polynomial or other approximation method would make the process of creating a sieve curve more arbitrary, because a decision has to be made on what curve would approximate the sieve curve best. For this reason the linear (on a semilog-scale plot) approximation of the sieve-curve is used.

The effect of the linear approximation of the sieve curve is expected to be the greatest in between data points. The linear approximation of the s-shaped curve will cause underestimation of the grain size for the lower half of the curve (up to 50% passing percentage) and overestimation of the grain size for the upper half. The uniformity coefficient $c_u$ thus has a positive bias, but the consequences for the $D_{50}$ are relatively small.

**Use of a master sample to represent the sediment composition of a transect**

The concept of master sample was applied to calculate the representative sediment composition per transect. Guillen and Hoekstra (1996); Medina et al. (1994) have also used this method and Medina et al. (1994) stated the hypothesis that a master sample of the active profile should not change in time. The master samples were used to better compare the different measurement campaigns as a higher number of samples in an area with coarser sediment will not lead to a higher average value in the transect if an other measurement campaign has only one sample in this area. A side effect of the master sample method is the large influence of the measured grain sizes at the offshore located measurement locations. The distance between measurement points at deeper water is usually larger and thus the weighing factor for these locations is larger. This is considered as a negative side effect as this larger weighing factor will enlarge the measurement errors at these locations and these are measured to be larger for the samples taken at deeper water.

**Data interpretation**

**Sample representing active processes**

In this research the assumption is implicitly made that the taken sediment samples represent
the active processes in the nearshore region. Though the thickness of the sample (5–10 cm) can well be more than the thickness of the active layer. This causes that variations in grain size between sample locations cannot be ascribed to differences in active processes alone. These differences could also be caused by differences in the layer beneath the active layer. In this case, at the Sand Motor the layer beneath the active layer consists of Sand Motor sediment (T1) what is considered to be relatively the same type of sediment, distributed over the Sand Motor area without significant spatial differences. At the Sand Motor, differences in grain size can thus be assigned to differences in grain size in the active layer, or a difference in the sample depth, causing a larger part of the sample to consist of Sand Motor sediment. For the measurement area outside the direct range of the Sand Motor (where the Sand Motor was constructed) (transects A,F,B) the native sediment under the active layer could influence the measurement. The grain sizes of native sediment in areas along the Dutch coast has large variations (see Section 2-3-3) in space. Variations in measured grain size outside the Sand Motor construction area could thus be caused by differences in sub layers instead of differences in grain size of material from the active layer.

Spatial differences in sediment composition
All differences in the sediment composition of measurement locations are interpreted to represent a spatial variation of the sediment composition. Though the standard deviation of the different sediment samples taken at the same location can be higher than the difference between the averages per location. The uncertainty of the average measured value per location is not taken into account in this research because the number of samples per location was too small to get statistically relevant information.

Influence of the differences in measurement set-up
The analysis of the evolution of the spatial distribution of sediment size and grading at the Sand Motor is based on the previously described data sets. These data sets have come about in a different way, making it not straightforward to compare them. The possible effect of the difference in used measurement methods and measurement areas is described below.

The use of different measurement techniques to procure the sediment data could lead to differences in the value of the parameters, for example by a bias in a measurement procedure. Not preparing the sediment samples of the T3 campaign before the sieving process has led to such a bias. For this reason the comparison of the absolute values of the different data sets is not that significant and focus is put on the study of the spatial distribution patterns.

The datasets of the measurements by Imares in October 2010 and August 2012 are compared to the measurements taken in February 2013 to analyse the change in time of the grain size parameters. The measurement locations used in these different campaigns differ, though some transects are located close to eachother. The measurement area of the T2 campaign is adjusted to match the area of the T3 campaign, but for the T0 campaign this was not possible as the bathymetry before the construction of the Sand Motor is not comparable to the situation after the construction of the Sand Motor. The measurements are therefore compared related to the water depth in the profile.

Measurement campaigns representing the temporal variation
The different measurement campaigns are used to indicate the development of the sediment distribution between these measurement periods. Though it should be noted that the development of the sediment composition is not a linear process. The sediment distribution of the top layer of sediment varies in timescales as short as half a wave-cycle (Clifton, 1969),
and at slightly longer time scales preceding extreme events in wave conditions or water levels influence the sediment distribution. The magnitude of the variations in sediment sorting for these short time scale processes are not known but the implicit assumption is made that these differences are smaller than the measured differences between the sediment distribution of the measurement campaigns. Otherwise the results of the measurement campaigns could not be used to indicate a development of the sediment composition.

Guillen and Hoekstra (1996) indicated that at Terschelling the natural variation of the sediment distribution in the nearshore area was larger than variation caused by the nourishment. However, in the measurements at the Sand Motor the difference between the Sand Motor area where sediment is nourished and the area North of the Sand Motor is apparent. This difference in sediment can partially be caused by the Sand Motor sediment itself and partially by the different hydrodynamics caused by the shape of the nourishment as expressed in Section 2-4-3. As the size and shape of the Sand Motor nourishment are not comparable to the shoreface nourishment studied by Guillen and Hoekstra it could be that the effect of this nourishment is larger than the natural variability.

The measured temporal variability is dependent on the thickness of the sediment sample as the thickness of the sample determines what amount of bed level change is taken account as active processes as described above.

4-7 Conclusions

Field data of several measurement campaigns was analysed to research how the sediment is sorted in the Sand Motor area. The comparison of the results of the different measurements campaigns shows the development of the sediment distribution in time. A graphical overview of the measured sediment sorting at the Sand Motor is presented in Figure 4-28. The following conclusions are drawn based on the presented and analysed field data:

- **The sediment used for the construction of the Sand Motor is significantly coarser than the native sediment in the area.**
  After construction of the Sand Motor the average median grain size in the area is also significantly coarser than in the natural situation. (Section 4-5-1)

- **After the construction of the Sand Motor a significant increase in sediment sorting in the longshore direction was measured.**
  The sediment at the Sand Motor has become relatively coarser and the sediment North of the Sand Motor has become relatively finer. When comparing the different median grain sizes of the T0 and T3 campaign the sediment has become coarser and finer in the absolute sense as well. (Section 4-5-3)

- **At the Sand Motor the sediment composition has become more sorted in time.**
  The uniformity coefficient for the Sand Motor transects was measured to be between 1.5 and 2 compared to values between 2 and 2.5 in the situation before the construction of the Sand Motor, see Figures 4-8, 4-12, 4-16.

- **The sediment sorting in the cross-shore direction has a minimum median grain size that moves offshore during high wave conditions**
In the cross-shore direction for all transects a shift of the relative minimum median grain size was observed for the different measurement campaigns. Before the construction of the Sand Motor the minimum grain size was located at -8m NAP, at T2 the minimum was found at -4m NAP and at T3 the minimum had shifted towards -5.3m NAP. (Figure 4-26)

- The Sand Motor influences the cross-shore sediment sorting.
  A distinction can be made in the development of the sediment distribution in the cross-shore direction at the Sand Motor and North of the Sand Motor, see Figure 4-27. Before the construction of the Sand Motor the sediment distribution in these areas was comparable. After the construction of the Sand Motor the Sand Motor transects contain coarse sediment (coarser than nearshore) at a water depth of 8–10m, where the transects North of the Sand Motor have an increased amount of fine material in this depth range.

**Figure 4-28: Graphical overview of measured sediment sorting at the Sand Motor**

### 4-8 Hypotheses

The conclusions presented in the previous section, together with knowledge on sediment transport processes, leads to the following hypotheses on the sediment transport and sorting mechanisms around nourishments:
• The absolute increase in the median grain size in the area where the Sand Motor is constructed is caused by the construction of the Sand Motor with sediment that was significantly coarser than the native sediment in this area.

• The increase in the alongshore sorting with relatively coarser sediment at the Sand Motor and relatively finer sediment North of the Sand Motor is expected to be caused by the shape of the Sand Motor. Waves focus at the head of the Sand Motor and the tidal current is stronger because of the contraction of the tidal current pattern at the Sand Motor. Especially finer sediment is stirred up by the waves and transported mainly northward, the mean direction of the tidal current. The finer sediment is deposited North of the Sand Motor due to a decrease in velocity of the alongshore currents in this area.

• The lower uniformity coefficient measured at the Sand Motor transects is expected to be caused by the erosion of especially the finer sediment fractions. This would match the second hypothesis that especially finer sediments are eroded at the Sand Motor.

• The evolution of the location of the minimum median grain size in offshore direction is expected to be caused by high wave conditions transporting the fine sediment offshore by the undertow. As the location of the minimum median grain size is located nearest to the shore in a period of low wave conditions (T2 - August 2012) and more offshore after a winter period (T3 - February 2013). The construction of the Sand Motor can have reset this process as the sediment distribution of the Sand Motor was initially uniform. That would also explain the location of the minimum median grain size of the undisturbed situation (T0) that was located the most offshore.

• The differences in cross-shore sediment sorting for the Sand Motor transects and the transects North of the Sand Motor can be caused by both the cross-shore sediment transport of Sand Motor sediment to larger depths and the longshore transport of the finer sediment described above. It is expected that relatively coarse sediment is transported in the cross-shore direction due to structural erosion of the nourishment. The finer sediment fractions might be transported especially alongshore and be partially deposited North of the Sand Motor. The coarser sediments might be transported by the undertow especially in high energy wave conditions and deposited in the deeper part of the profile (8–10 m NAP).
Chapter 5

Modelling of sediment sorting in the cross-shore direction at a nourishment

5-1 Introduction

The numerical model Delft3D is used to simulate the sediment sorting processes and time scales in the cross-shore direction at a large scale nourishment. A cross-shore model (2Dv) is set-up and used for the simulation of different scenarios to research the effect of different environmental parameters on the sediment distribution. The numerical model Delft3D is introduced in Section 5-2. In Section 5-3 the set-up of the specific model used for the simulations is introduced and the limitations of the use of a 2Dv model to model sediment sorting at the Sand Motor are explained in Section 5-4. Finally, in Section 5-5 and 5-6 the modelled scenarios and the results of these scenarios are presented. The results are discussed (Section 5-7) and conclusions are drawn in Section 5-8.

5-2 Numerical model Delft3D

5-2-1 Introduction

Delft3D is a process-based numerical model suite. It is suitable for modelling flow phenomena with significantly larger horizontal length and time scales compared to the vertical scales, e.g. shallow seas, coastal areas, estuaries, lagoons, rivers and lakes (Deltares, 2011).

Delft3D is composed of different modules that can compute the hydrodynamics, waves, sediment transport, morphology, water quality and ecology. The base of the model is the hydrodynamic module, Delft3D-FLOW, that solves the unsteady shallow water equations in two (depth-averaged) or three dimensions, these include the horizontal momentum equations, continuity equation, transport equation and a turbulence closure model (Lesser et al., 2004).
Waves are simulated by the Delft3D-WAVE module that is based on the spectral wave model SWAN (Simulating WAves Nearshore), which computes the evolution of random short-crested wind-generated waves in coastal areas. This module can be coupled with the FLOW module through a dynamic interaction, where the output of each module is used as an input on the other, accounting for the effects of waves on currents and the effect of flow on waves.

The sediment transport is calculated based on the hydrodynamics, the type of sediment, the availability of sediment and the presence of sediment sources or sinks. Sediment transport gradients (and sources or sinks) imply bed level change. The bathymetry is updated and the updated bathymetry is used in the hydrodynamic computation of the next time step. Often a multiplication factor for the bed change is used to speed up these processes in relation to the hydrodynamics (Lesser et al., 2004; Roelvink, 2006; Ranasinghe et al., 2011).

5-2-2 Hydrodynamic equations

The equations for flow in Delft3D are based on the Navier-Stokes equations and are transformed for the application in coasts, rivers and estuaries.

The Navier-Stokes equations describe the motion of fluids. The equations can be derived with the use of Newton’s second law (momentum equation) and the conservation of mass (continuity equation). These equations can be simplified to solve the flow of water in typical Delft3D situations. The most important and relevant simplifications are listed below.

- The pressure is assumed to be hydrostatically distributed. Thus vertical accelerations are assumed to be small compared to the gravitational acceleration and are therefore not taken into account (Deltares, 2011). This assumption is valid if the characteristic horizontal lengths scales are much larger than the characteristic vertical length scale and the characteristic vertical velocity is small in comparison with the characteristic horizontal velocity. In the application area of Delft3D (coasts, estuaries, rivers, tidal basins) the horizontal length scales are typically much larger than the vertical scale.

- The Boussinesq approximation is applied, stating that if density variations are small the density may be assumed constant in all terms except the gravitational term.

- The viscosity of the water is constant, as water is a Newtonian fluid.

- The Navier-Stokes relations are Reynolds averaged and small scale turbulence features are approximated with Reynolds stresses, as the grid is usually too coarse to resolve the fluctuations (Deltares, 2011).

5-2-3 Sediment transport equations

The transport of sediment (and heat, salinity, other substances) is modelled in Delft3D by an advection-diffusion equation in three dimensions. In case of supply or withdrawal of a substance a source or sink term can be included.

For the transport of sediment some extra processes are important that are not of importance in case of other constituents (e.g. heat). Sediment has an exchange between the bed and the...
5-2 Numerical model Delft3D

flow, sediment particles settle under the action of gravity, and a sediment transport gradient causes erosion which in turn influences the hydrodynamic calculations. Furthermore, sediment fractions could interact and influence the settling velocity or the critical shear velocity (e.g. hiding and exposure in the bed).

5-2-4 Computational grid

**Horizontal grid: Staggered grid**

Delft3D uses a staggered grid to discretize the 3D shallow water equations in space, see Figure 5-1. The water level ($\zeta$) is defined in the centre of a computational grid cell $(m,n)$. The velocity components $(u,v,w)$ are defined on the faces of this cell $(m+1/2, n; m, n+1/2, etc.)$, in a perpendicular direction on this face. The water depth $(d)$ is defined in the corners of a cell $(m+1/2, n+1/2, etc.)$. The numerical grid of Delft3D defines a computational control volume. The depth is defined at the corners of all the computational grid cells, so also at the corners of this control volume, see Figure 5-2.

![Figure 5-1: Definition of model parameters on the staggered grid, 3D view (left), top view (right) (Deltares, 2011)](image1)

**Vertical grid: $\sigma$-layers**

Delft3D has two options to implement a grid in the vertical direction using $\sigma$-layers, following the bathymetry of the model, or strictly horizontal layers called z-layers., see Figure 5-3.

The $\sigma$-coordinate grid has a constant user-defined number of layers in the vertical, with a varying distribution of layer thicknesses. This allows for more resolution in zones of interest, for example near the surface and near the bed. The z-grid is only preferred over the $\sigma$-grid if one is modelling pycnoclines in regions with strongly stratified flow over steep topography. In this model the density differences in the water column due to salinity and temperature differences are ignored, so the $\sigma$-grid is used.
5-2-5 Boundary conditions

The model in Delft3D does not have the same dimensions as the modelled area. The grid consisting of the modelled area has to be enclosed by a so-called grid enclosure to be able to supply the necessary gradients at the boundaries.

The boundaries of the model can either be open or closed and by default are set on closed. A closed boundary means that there is no flow through the boundary possible, representing a land-water line for example. An open boundary means that there is water flowing through the boundary, and the boundary condition says something about the amount. It is possible to define a certain discharge, water level, velocity or water level gradient at the boundary. Describing boundaries in the form of a water level calls for an artificial ‘ghost’ cell outside the boundary where the boundary water level can be defined. The line through these water level points, located just outside the first or last computational control volume is called the (external) grid enclosure. This is visualized in Figure 5-4. It should be noted that the location inside the computational cell differs according to what type of boundary condition is used. Using a water level boundary condition will lead to a larger area than using a velocity or discharge based boundary condition (half a grid size larger area).

Figure 5-3: Vertical computational grid outline of the Z-model (left) and the σ-model (right) (After: Deltares (2011))
Neumann boundary condition

The Neumann boundary condition is a type of open boundary condition, meaning that on both sides of the boundary water is present. Neumann boundaries can only be applied on cross-shore boundaries in combination with a water level boundary at the offshore boundary, which is needed to make the solution of the mathematical boundary value problem well-posed. The Neumann boundary condition imposes a water level gradient in the alongshore direction. In case of tide or when a storm travels along a coast the alongshore gradient varies in time, but in a model with a limited cross-shore extent, the alongshore gradient of the water level does not vary much in cross-shore direction. A constant periodical water level gradient for a boundary can be applied to models with a limited cross-shore extent, under the assumption that the alongshore gradient of the water level does not vary much in cross-shore direction (Deltares, 2011). If the tidal wave component is travelling in positive x-direction, the phase difference between the water level and Neumann boundary is $\pi/2$ (=$+90^\circ$). If the tidal wave component is travelling in negative x-direction, the phase difference is $-\pi/2$ (=$-90^\circ$). This means that the water level gradient is zero at maximum tidal elevation and zero at slack water.

5-2-6 Bed stratigraphy

Implementation of a layered bed stratigraphy, layers with different grain size parameters, is possible in Delft3D. The initial thickness of different layers can vary spatially as well as the sediment composition. The sediment characteristics of these layers can be defined as a combination of different sediment fractions.

The sediment at the bed is divided in a number of layers to keep track of the sediment composition in each layer separately. The top layer of the bed is the active layer that can erode or accrete and is called the transport layer, see Figure 5-5. In case of erosion only...
sediment particles from this active layer can be transported. In case of accretion, deposited sediment particles are mixed with the active layer. The transport layer shifts downward or upward for erosion and deposition respectively. In both cases the assumption is made that sediment within a layer is homogeneously mixed.

Figure 5-5: Schematic representation of sediment stratigraphy in Delft3D in case of deposition of sediment. The yellowish top layer is the transport layer, the other brownish layers are the underlayers.

5-3 Set-up of cross-shore model

In this section the set-up of the used model will be explained. The following subjects will be treated sequentially: the dimensions of the grid, the bathymetry, the sediment composition of the bed, the used transport formulation, the boundary conditions and the use of the wave roller module and the input of wave conditions.

5-3-1 Grid

The area researched is a cross-shore transect at the center of the Sand Motor. The model is oriented in cross-shore direction and in depth, so it has 2 dimensions with a vertical orientation (2Dv). In the alongshore direction no variation is possible within the grid as the grid is one gridcell wide. The model grid is located at the location of the transect at the center of the Sand Motor corresponding to transect D in the February 2013 campaign, see Figure 5-6.

The grid stretches to a depth of -20 meter (relative to NAP) in the offshore direction. This results in an almost double grid length compared to the measurement area, that runs to a depth of -11 m (NAP). The possibility to impose the measured wave conditions at the Europlatform at this boundary is the reason for the extended grid size. The Europlatform is located off shore meaning that the waves are not influenced by the coast, the waves have not shoaled or refracted, what would be the case at -11 m deep. A depth of 20 meter is considered deep enough to assume that the waves of the Europlatform have not altered much due to the mentioned processes (shoaling and refraction). In the near shore direction the grid is large enough to enclose the water line after a simulation period of about 1.5 years.
In the y-direction (cross-shore) the length of the grid cells varies according to the expected variation in the cross-shore at that location. In the active and mobile surfzone the grid size is therefore the smallest, 5 m, and more offshore where the bed level is not expected to change the grid size is 20 m. The dimensions of the grid cells are a constant 50 m in the x-direction (alongshore). In the vertical direction the $\sigma$-layer grid is used with 12 layers, all dimensioned with a constant but different percentage of the water depth. A logarithmic distribution of the layers is used to have a high resolution near the bottom, see Figure 5-7.

5-3-2 Bathymetry

The area of the Sand Motor is very dynamic in the sense of changes in bed level. The newly constructed coastline at the location of the Sand Motor retreats and the profile shape changes in time.

The first bathymetric survey of Shore monitoring after the Sand Motor construction interpolated with JARKUS data resulted in the depth profile of the transect in August 2011 (T1). The measured depth profile is extrapolated to a depth of -20 m (NAP) water depth because bathymetric data for this area was lacking.

The measured bed level development of the modeled transect is presented in Figure 5-8 for the moments corresponding to the field measurement campaigns (T2: August 2011, T3: February 2013). Apart from these measured profiles two extreme linear profiles were designed to be
used in the model experiment, a steep profile with a slope of 4.3% and a gentle profile with a slope of about 1.4%.

Figure 5-8: Bathymetry measured at transect D (T1: August 2011, T2: August 2012, T3: February 2013) and designed slopes for model input

5-3-3 Sediment composition

The sediment composition of the bottom at the Sand Motor can be approximated by the sediment composition at transect D of the different measurement locations.

The transport layer thickness is a constant 0.1m. The thickness of each underlayer is set on 0.2 m. For all sediment fractions the following model parameters are constant:

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cref</td>
<td>1.60E+03</td>
<td>Reference density for hindered settling calculations [kg/m³]</td>
</tr>
<tr>
<td>IopSus</td>
<td>0</td>
<td>(&quot;0&quot;/&quot;1&quot;) Suspended sediment size does/do not depend on local flow and wave conditions</td>
</tr>
<tr>
<td>SedTyp</td>
<td>sand</td>
<td>(&quot;sand&quot;, &quot;mud&quot; or &quot;bedload&quot;) Type of sediment</td>
</tr>
<tr>
<td>RhoSol</td>
<td>2.65E+03</td>
<td>Specific density [kg/m³]</td>
</tr>
<tr>
<td>CDryB</td>
<td>1.60E+03</td>
<td>Dry bed density [kg/m³]</td>
</tr>
</tbody>
</table>

The difference between the sediment fractions is the sediment diameter and the FacDss, the factor for the initial suspended sediment diameter, which depends on the sediment diameter. For each sediment fraction the median sediment diameter is given (SedDia) as well as the boundaries of the fraction class (SedMinDia and SedMaxDia), otherwise the tails of the lognormal distribution would extend beyond these borders leading to a different sediment composition. The factor for the initial suspended sediment diameter, FacDss, can vary between 0.6 and 1.0 and is inversely related to the sediment size. The FacDss is therefore put to 1.0 for sediment fractions with a median smaller than 200 µm, to 0.6 for sediment
fractions with a median diameter larger than 500 $\mu m$, and to 0.8 for sediment fractions in between.

**Measured sediment compositions**

Sediment compositions are obtained by analysis of the measurement results in August 2011 (T1), August 2012 (T2) and February 2013 (T3). The grain size parameters of the two first campaigns were rewritten to create weight percentages for the same classes as the February 2013 measurements: the British Sieving classes. The percentages of sediment in the smallest class (median 31.5 $\mu m$) were neglected because the particles in this class will be in permanent suspension in the coastal environment and therefore need to be taken into account. The largest class is grouped with the second largest class to make a class with the median of the second largest class (512.5 $\mu m$) but with the extent to the border of the largest sediment class measured: 1.18 mm.

**Table 5-1:** Sediment classes used as model input

<table>
<thead>
<tr>
<th>Median value of fraction [$\mu m$]</th>
<th>Aug 2011 (S1)</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
<th>Aug 2012</th>
<th>Feb 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>106.5</td>
<td>8.75</td>
<td>18.54</td>
<td>5.79</td>
<td>16.72</td>
<td>8.33</td>
<td>1.23</td>
</tr>
<tr>
<td>181.0</td>
<td>19.62</td>
<td>15.15</td>
<td>11.87</td>
<td>26.00</td>
<td>17.81</td>
<td>6.83</td>
</tr>
<tr>
<td>256.0</td>
<td>28.33</td>
<td>19.64</td>
<td>26.00</td>
<td>28.39</td>
<td>25.56</td>
<td>27.94</td>
</tr>
<tr>
<td>362.5</td>
<td>23.39</td>
<td>15.36</td>
<td>29.18</td>
<td>22.27</td>
<td>22.35</td>
<td>39.19</td>
</tr>
<tr>
<td>512.5</td>
<td>15.94</td>
<td>31.31</td>
<td>27.16</td>
<td>6.62</td>
<td>25.95</td>
<td>24.81</td>
</tr>
</tbody>
</table>

**Designed sediment compositions**

Sediment compositions with the following characteristics compared with the measured sediment composition at T1 have been designed:

- S2. same D$_{50}$, larger c$_{u}$
- S3. larger D$_{50}$, same c$_{u}$
- S4. smaller D$_{50}$, same c$_{u}$

The sieve curves are based upon the D$_{n}$ diameters of the T1 measurement results. From these sieve curves the weight percentages of the fractions of the British Standard were obtained. An overview of the weight percentages of these designed sediment compositions and the measured sediment compositions is listed in Table 5-1. See Figures 5-9 and 5-10 for an illustration of the different sediment compositions that will be used in the model.
5-3-4 Transport formulation

The transport formulation of Van Rijn of 2004 is used to calculate the sediment transport. This formulation calculates the bed load transport and the suspended sediment transport separately. The bed shear stress is calculated with the Van Rijn (2004) roughness predictor.

Default values for the calibration factors on the wave-related suspended-load and bed-load transport (SusW and BedW) are used, so the transport is not calibrated. Calibration of the transport would have been useful to be able to quantitatively compare the measured sediment sorting with the modelled values. Though the model is useful for its main goal: to research the processes determining sediment transport and the relative influence of different parameters.

The longitudinal and transverse bed slope gradients ($\alpha_{bs}$ and $\alpha_{bn}$) were both set to 20 instead of the default 1 and 1.5 respectively. The goal and result of these higher factors was to stabilise the morphodynamics of the model in the swash zone.

The additional keywords with which the Van Rijn (2004) sediment transport formula and bed roughness predictor are applied are listed here:

- Trafrm = #vrijn04.frm# transport formulation
- Trtrou = #N# (default) Trachytope option de-activated
- BdfRpC = 1.0 (default) ripple calibration factor
- BdfRpR = 0 (default) ripple relaxation time
- BdfMrC = 0 (default) megaripple calibration factor
- BdfMrR = 0 (default) megaripple relaxation time
- BdfDnC = 0 (default) dune calibration factor
- BdfDnR = 0 (default) dune relaxation time

5-3-5 Boundary conditions

The grid has four boundaries. The boundary at the Sand Motor (depth=+4 m NAP) is a closed boundary, the other boundaries are open boundaries, see Figure 5-11. Via these open
boundaries hydraulic conditions are imposed. Sediment transport concentrations are not imposed at the boundaries, but a Neumann-type boundary condition is used for the sediment transport.

The tide influences the hydraulic boundary conditions in two ways: it influences the water level imposed on the ‘sea’ boundary, and it causes the water level gradient imposed as a Neumann boundary condition on the ‘north’ and ‘south’ boundary conditions. Both the water level and the water level gradient vary in time. In the next sections the data and the model input of these boundaries is presented.

Figure 5-11: Top view of model grid and boundaries called ‘Sea’, ‘North’ and ‘South’. Note that the dimensions of the grid in the figure are not proportional to the grid dimensions.

Water level boundary conditions

The variation in water level is based on the measured water level at the Europlatform in the same time period as the 2Dv model runs. The measured water level at the Europlatform contains both the tidal elevation as any water level variations due to wind set-up or set-down (Figures 5-12).
Neumann boundary conditions

In the alongshore direction a water level gradient is present because of the tidal wave. This water level gradient is imposed on the model by Neumann boundary conditions on the cross-shore boundaries (‘north’ and ‘south’). The magnitude of this water level gradient in time is deduced from a 2Dh model simulation of the Sand Motor area by Arjen Luijendijk employed by Deltares. The difference between the water level elevation on the South and the North side of the transect divided by the distance of these points results in the water level gradient. This deduction of information on the water level gradient resulted in an artificial time series of the Neumann boundary condition for a period of 10 tidal periods, the useful runtime of the 2Dh Sand Motor model. This series is repeated to cover the runtime of the 2Dv Sand Motor transect model.

The water level gradients deducted in the above described manner at the most offshore measurement location (D11) and a location closer to the shore (D07) are compared, see Figure 5-13. Although these locations are not more than 500 meter apart there is a considerable difference in gradients and this is implemented in the boundary conditions. The water level gradient based upon the model output values at D11 is used as model input for the most offshore point of the north and south boundary and the water level gradient at D07 is used for the coast ward side of the north and south boundary. The water level gradient at the north side and the south side of the transect is represented by the same value and the same variation in time.

The high frequency fluctuations in the signal of the Neumann boundary conditions are smoothed to prevent these rapid fluctuations to cause instabilities in the model. In the smoothed signal the peaks of the original signal together with data at regular intervals (8 timesteps) are interpolated using a cubic interpolation method. The result of this method and the original signal are presented in Figure 5-14.
5-3 Set-up of cross-shore model

Figure 5-13: Water level gradient in longshore direction at two different locations in the transect. Location D07 is located more nearshore. The gradient is calculated based on water level data of a 2Dh Delft3D model of the Sand Motor area.

Figure 5-14: Modelled water level gradient and smoothed signal. Cubic interpolation is used to make a function of a selection of data points, including the minima and maxima.

5-3-6 Wave roller module

The Wave roller module of Delft3-FLOW is used. The Wave roller module applies waves at the boundary and does not calculate the effect of wind on the wave spectrum. As the size of this model is small, the assumption of waves not being reshaped or created by wind within the model area is valid. The Wave roller model consists of one balance equation for the short wave energy, and another one for the roller energy (Briere et al., 2011). Dissipation due to wave breaking is computed according to the formulation of Roelvink (1993), which is an extension of the model of Battjes and Janssen (1978). A time series of waves is imposed on the open model boundary and these waves travel through the model towards the coast. The wave height is prescribed at this boundary and the wave may not be breaking or start breaking at the boundary. In this type of stationary mode the FLOW-manual (Deltares, 2011) recommends using a water level boundary offshore and Neumann boundaries for the lateral boundaries. Also the keyword Cstbnd = #yes# is added to avoid the formation of artificial boundary layers along the domain boundaries. All of the above recommendations have been applied in the model. The roller model in stationary mode is activated with the keyword: Roller = #yes# and the following roller model parameters:

\[
\begin{align*}
\text{Betaro} & = 0.05 \quad \text{Slope } \beta \text{ of the wave front on which the roller acts} \\
\text{Gamdis} & = -1 \quad \text{Breaker parameter } \gamma \\
\text{F_lam} & = -2.0 \quad \text{Breaker delay parameterization} \\
\text{Fwee} & = 0.01 \quad \text{Bottom friction factor}
\end{align*}
\]

The keyword: Snelli = #yes# is also used to apply Snell’s law within the boundaries of the domain. This keyword is used to refract the waves towards the shore, though in this case angle of incidence of the waves is already perpendicular to the coast.
5-3-7 Wave conditions

The waves are introduced in the open boundaries of the model. The measured wave conditions at the Europlatform are used as data. This dataset contains hourly data of the significant wave height, period and direction.

Figure 5-15: Wave rose of wave conditions at Europlatform during the simulation period (July 2011 - February 2013). The length of the bins shows the percentage of occurrence of that wave direction, the color of the bins shows the (relative) percentage of occurrence of the different wave heights.

The wave data measured at the Europlatform contains waves from all directions, so including waves coming from the ‘shore’ and waves approaching the shore parallel, see Figure 5-15 and imagine the Holland Coast in this picture. Especially waves running parallel to the shore caused instabilities within the 2Dv model. To solve this problem the wave direction of all waves was changed to a direction perpendicular to the shore (320.12°).

The recorded wave heights at the Europlatform are adjusted based on the original wave direction measured at that location. The wave height of waves approaching from an angle of 0 to 180° are reduced to zero. Waves approaching with a small angle to the shoreline are reduced based on the theory of wave energy conservation, leading to Equation 5-1. The measured wave conditions and the adjusted wave conditions used in the model are presented in Figure 5-16.

\[
H_{s,\perp} = \sqrt{\sin \alpha} H_{s,m} \tag{5-1}
\]

- \(H_{s,\perp}\) = Significant wave height perpendicular to the shore [m]
- \(\alpha\) = Angle of incidence relative to the shore orientation[^°]
- \(H_{s,m}\) = Significant wave height measured at Europlatform
The most severe wave conditions since the construction of the Sand Motor occurred in December 2011, with significant wave heights of over 5 meters (Figure 5-17). The measured wave conditions in this period are used as model input for wave conditions during a storm. The most calm wave conditions since the construction of the Sand Motor occurred in August 2012, with all wave heights under 1 meter (Figure 5-18). The measured wave conditions in this period are used as model input for calm wave conditions.
5-4 Limitations of the use of a 2Dv model

The orientation of the numerical model as two-directional model in the vertical direction (2Dv) has consequences for the behaviour and the possible applications of the model.

A 2Dv model uses the assumption that the model is placed along a longshore uniform coast. As the grid is only 1 grid cell wide no variations within the model are possible, and the surroundings are assumed to be identical to the grid itself. In reality the location of the Sand Motor is most likely the least longshore uniform location along the Holland Coast as the curvature of the Sand Motor is larger than the in general straight or gradually arching Holland Coast.

The assumption of an alongshore uniform ‘Sand Motor’ coast has consequences for processes that are based on alongshore variations:

- No coastline retreat or advance
  Structural erosion or deposition causing coastline retreat or advance is caused by alongshore gradients in the sediment transport rate. The lack of this alongshore gradient in the model, because of the alongshore uniformity, means that no coastline retreat or advance can be simulated. In reality the sediment transport gradients vary along the Sand Motor and the coastline of the Sand Motor retreats due to structural erosion. The lack of the simulation of the structural erosion of the Sand Motor profile leads to a development of the bed level that is not present at the Sand Motor. The sediment distribution is influenced by this bed level change and will thus not match the sediment distribution at the Sand Motor.

- No development of breaker bars
  A breaker bar is developed at the point where offshore transport stops and becomes onshore transport, located at the end of the surfzone (see Section 2-2-2). The processes influencing the bar formation and propagation are wave asymmetry, the return flow and the transport due to bound long waves. A Delft3D 2Dv model has vertical layers and can thus model most cross-shore processes with vertical variations, but the bound long waves are not incorporated in Delft3D. Furthermore, transport factors (e.g. the wave-related bed load and suspended load factors, BedW and SusW) influence the sediment transport and the possible bar formation.
  The correct representation of bar morphology in a Delft3D 2Dv model does not come naturally, and without calibration of parameters to lead to a correct representation of the bars, the morphology will most likely not be alike the modelled reality.
  As a consequence of the lack of (correct) bar morphology the local variations in grain size parameters due to the hydrodynamics around bars will not be present in the model results.

5-5 Modelled scenarios

In this section the different runs that will be executed with the model are presented and explained. The first group of model runs has three input parameters in which they differ: wave conditions, initial bathymetry and initial sediment composition. The results of these
different model runs will give an indication of the parameters influencing the sediment sorting process and the time scale on which this takes place. A few extra model runs are performed to test the sensitivity of the model to model parameters: the bed gradient factors for bed load transport and the thickness of the underlayer and transportlayer.

1. Wave conditions
   The wave conditions are probably the most important forcing mechanism for the transport of sediment in the cross-shore direction and therefore also for the sorting processes in the cross-shore direction. Both measured and artificial wave conditions are imposed on the model. The artificial conditions consist of a single wave height and period for the entire simulation time.

2. Bathymetry
   The shape and the depth of the bathymetry of the nourishment will influence the transport processes and also the sorting processes. For example a steeper slope will be more prone to erosion and small sediment particles will be eroded especially. Apart from the original bathymetry of the Sand Motor (measured in August 2011), the influence of the bathymetry will be tested with 2 other measured bathymetries and 2 linear slopes.

3. Sediment composition
   The sediment composition used as model input has a direct link to the sediment sorting within the transect during the simulation period. The sediment composition of the sediment used to construct the Sand Motor is used as input sediment composition for most model runs, but the influence of the sediment composition is researched with variations on this composition.

4. Comparison with measurements
   Two model runs are set-up to see if the model is capable of calculating the general order of magnitude of the sediment characteristics and the spreading along the transect. The model runs consist of the bathymetry and sediment composition measured in February 2013, the difference between the runs is the disabling of the morphological updating in the second run. The morphological updating is disabled as the morphology created by Delft3D is not realistic (see Section 5-4) and thus the results without morphological updating would perhaps represent the measured situation better. The outcomes of these model runs will be compared with the measurement results of the February 2013 campaign.
Table 5-2: Model runs to assess the influence of environmental parameters on sediment sorting patterns and time-scales

<table>
<thead>
<tr>
<th>Run</th>
<th>Wave Conditions</th>
<th>Bathymetry</th>
<th>Sediment composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>Dec-11</td>
<td>Aug-11</td>
<td>Aug-11</td>
</tr>
<tr>
<td>W2</td>
<td>Aug-12</td>
<td>Aug-11</td>
<td>Aug-11</td>
</tr>
<tr>
<td>W3</td>
<td>Hs = 3 m</td>
<td>Aug-11</td>
<td>Aug-11</td>
</tr>
<tr>
<td>W4</td>
<td>Hs = 0.5 m</td>
<td>Aug-11</td>
<td>Aug-11</td>
</tr>
<tr>
<td>B1/W1</td>
<td>Dec-11</td>
<td>Aug-11</td>
<td>Aug-11</td>
</tr>
<tr>
<td>B2</td>
<td>Dec-11</td>
<td>Steep Profile</td>
<td>Aug-11</td>
</tr>
<tr>
<td>B3</td>
<td>Dec-11</td>
<td>Gentle Profile</td>
<td>Aug-11</td>
</tr>
<tr>
<td>S1/W1</td>
<td>Dec-11</td>
<td>Aug-11</td>
<td>Same $D_{50}$, larger $c_u$ as Aug-11</td>
</tr>
<tr>
<td>S2</td>
<td>Dec-11</td>
<td>Aug-11</td>
<td>Larger $D_{50}$, same $c_u$ as Aug-11</td>
</tr>
<tr>
<td>S3</td>
<td>Dec-11</td>
<td>Aug-11</td>
<td>Smaller $D_{50}$, same $c_u$ as Aug-11</td>
</tr>
<tr>
<td>S4</td>
<td>Dec-11</td>
<td>Aug-11</td>
<td>Smaller $D_{50}$, same $c_u$ as Aug-11</td>
</tr>
<tr>
<td>C1</td>
<td>Feb-13</td>
<td>Feb-13</td>
<td>MorUpd = true</td>
</tr>
<tr>
<td>C2</td>
<td>Feb-13</td>
<td>Feb-13</td>
<td>MorUpd = false</td>
</tr>
</tbody>
</table>

5. Model parameters
The model parameters that are varied in the model runs series AB and SR are estimated and held constant for the model runs described before. These model runs are performed to assess the sensitivity of the model for variations of these parameters. When other values for the model parameters do not influence the model results much the model is not sensitive to this parameter and the uncertainty in the estimation of this parameter does not affect the conclusions from the model results.

The $\alpha_{bs}$ and $\alpha_{bn}$ parameters are bed gradient factors for the bed load transport in the longitudinal and transverse direction. The default settings of these parameters in Delft3D is 1 and 1.5 respectively, but a constant value of 20 was chosen for all model runs for the sake of stability. The values of $\alpha_{bs}$ and $\alpha_{bn}$ are varied according to the overview in Table 5-3 to see how sensitive the model is for these deviations.

Table 5-3: Model runs with varying parameters $\alpha_{bs}$ and $\alpha_{bn}$ to assess the sensitivity of the model for these parameters

<table>
<thead>
<tr>
<th>Run</th>
<th>$\alpha_{bs}$</th>
<th>$\alpha_{bn}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB1/W1</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>AB2</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>AB3</td>
<td>5</td>
<td>7.5</td>
</tr>
<tr>
<td>AB4</td>
<td>50</td>
<td>75</td>
</tr>
</tbody>
</table>

The thickness of the different layers in the sediment stratigraphy can influence the sediment composition of the bookkeeping layers (underlayers) and the transportable
layer. A larger thickness of the transportlayer is expected to slow down or average out sediment sorting processes as changes in the sediment composition are averaged over a larger sediment layer. The thickness of the underlayer could be of importance in cases where erosion and deposition alternately occur at one location. As the layers beneath the toplayer are ‘saved’ as the sediment composition of the sediment within the thickness of the underlayer. The thickness of the underlayer and the transportlayer are varied to see what the influence of this model parameter is on the sediment composition. Table 5-4 presents an overview of the simulations.

**Table 5-4:** Model runs with varying layer thicknesses to assess the sensitivity of the model for these parameters

<table>
<thead>
<tr>
<th>Run</th>
<th>UnderLayer [m]</th>
<th>TransportLayer [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>SR1</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td>SR2</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>SR3</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>SR4</td>
<td>0.2</td>
<td>0.05</td>
</tr>
</tbody>
</table>

5-6 Model results

The results of the model runs described in the previous section are used to answer the research questions. The variation of the median diameter ($D_{50}$) and the uniformity coefficient ($c_u$) are researched in space and time and compared to the measurement results to answer the following questions:

1. How is sediment sorted in the cross-shore profile?
   (a) What is the characteristic sediment sorting pattern?
   (b) What is the influence of the design of the nourishment on the sediment distribution?
   (c) What is the influence of hydraulic conditions on the sediment sorting distribution?
   (d) What are the time scales of different types of evolution of the sediment distribution in the cross-shore?
   (e) Are the model results qualitatively comparable to the measured cross-shore sediment distribution?

2. Are the model results qualitatively comparable to the measured cross-shore sediment distribution?

3. How sensitive is the model to deviations in model parameters?

5-6-1 Sediment sorting pattern in the cross-shore profile

The results of different scenarios appear to have the same sediment sorting pattern in the cross-shore profile. Figure 5-19 shows the median grain size diameter and cumulative sedimentation...
and erosion in the profile after a simulation of one month of scenario W1. Scenario W1 has the initial bathymetry and sediment composition measured in August 2011, just after construction of the Sand Motor. The wave conditions of scenario W1 are the cross-shore components of the significant wave height of the measured waves at the Europlatform in December 2011, a month with a couple of storm events, see Section 5-3-7.

The following characteristics of the relation between median grain size and erosion and sedimentation are observed (see Figure 5-19):

1. A local minimum in the median grain size is located at the turning point of erosion and sedimentation.
2. The absolute minimum median grain size is located just offshore of where the profile accretes.
3. An offshore situated local maximum of median grain size is located at the location of maximum sedimentation.
4. Larger than average median grain sizes are found in the area of the profile where the original slope is reworked to a more gentle slope.

More research is needed to specify in what cases this sediment sorting pattern is found apart from the researched wave conditions in these simulations and this specific measurement moment. It is expected that this specific sorting pattern corresponds to the sediment sorting at not energetic conditions after a period of high waves. The sediment sorting pattern will probably be different during high wave conditions and during a long period of low energy wave conditions as well. Furthermore, it is expected that this characteristic sediment sorting pattern is not found in the initialisation period, as the modifications in the initial profile are large and it takes some time for the initial uniform sediment distribution to develop.
5-6-2 Influence of nourishment design on sediment sorting pattern

The design of the nourishment in this 2Dv model is varied in terms of the (1) bathymetry and the (2) sediment composition of the nourishment. The hydraulic forcing of the scenarios in this section is the same as for scenario W1: the December 2011 storm conditions. The influence of the variations in the nourishment design on the sediment sorting pattern introduced in the previous section is described in this section.

Influence of initial bathymetry on sediment distribution

Three scenarios with different initial bathymetries are researched to see the effect of the initial slope of a nourishment on the sediment sorting processes (Table 5-5). These bathymetries are described in section 5-3-2.

<table>
<thead>
<tr>
<th>Run</th>
<th>Wave Conditions</th>
<th>Bathymetry</th>
<th>Sediment composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1/W1</td>
<td>Dec-11</td>
<td>Aug-11</td>
<td>Aug-11</td>
</tr>
<tr>
<td>B2</td>
<td>Dec-11</td>
<td>Steep Profile</td>
<td>Aug-11</td>
</tr>
<tr>
<td>B3</td>
<td>Dec-11</td>
<td>Gentle Profile</td>
<td>Aug-11</td>
</tr>
</tbody>
</table>

It is expected that the slope of the nourishment will influence the transport processes and thus also the sorting processes. For example a steeper slope will be more prone to erosion and small sediment particles will be eroded especially and be deposited at a more gentle slope according to Dean’s theory on the equilibrium profile.

The results of the scenarios with extreme initial nourishment slopes show the same sorting characteristics related to the sedimentation and erosion in the profile as described in Section 5-6-1, see Figure 5-20. Though the absolute location in the profile of these grain size minima and maxima differs as the initial bathymetry is different. The relative location of sediment sorting characteristics, related to the amount of sedimentation and erosion, is the same for these scenarios.

The extreme values of the median grain size of the different scenarios do not differ much, although the differences in the bed level changes are large. The maximum sedimentation is about 5m in the steep profile compared to 1m sedimentation in the gentle profile and the maximum $D_{50}$ of steep profile is 5 $\mu m$ larger, and the minimum $D_{50}$ of the gentle profile is 5 $\mu m$ smaller. In the result of the gentle profile a small local minimum in the $D_{50}$ is visible in the swash zone of the profile.
Modelling of sediment sorting in the cross-shore direction at a nourishment

Figure 5-20: Sediment distribution after one month simulation, related to sedimentation and erosion, for different initial bathymetries. (B2: steep profile, B3: gentle profile)

Influence of initial sediment composition on sediment distribution

Four model runs are set up to research the effect of the initial sediment composition on the sediment distribution. The set-up of these sediment compositions is described in section 5-3-3 and these scenarios with different sediment composition are listed in Table 5-6.

Table 5-6: Modelled scenarios with a different initial sediment composition

<table>
<thead>
<tr>
<th>Run</th>
<th>Wave Conditions</th>
<th>Bathymetry</th>
<th>Sediment composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1/W1</td>
<td>Dec-11</td>
<td>Aug-11</td>
<td>Aug-11</td>
</tr>
<tr>
<td>S2</td>
<td>Dec-11</td>
<td>Aug-11</td>
<td>Same D50, larger c_u as Aug-11</td>
</tr>
<tr>
<td>S3</td>
<td>Dec-11</td>
<td>Aug-11</td>
<td>Larger D50, same c_u as Aug-11</td>
</tr>
<tr>
<td>S4</td>
<td>Dec-11</td>
<td>Aug-11</td>
<td>Smaller D50, same c_u as Aug-11</td>
</tr>
</tbody>
</table>

It is expected that the resulting sediment composition increases proportional to the mean grain size of the input sediment composition. Furthermore it is expected that the simulation with sediment with a larger grading will lead to larger maxima and smaller minima, as the average sediment composition contains more fine material and more coarse material.

The results of the scenarios with a different initial sediment composition show the same sorting characteristics related to the sedimentation and erosion in the profile as described in Section 5-6-1. The model results show an almost identical bed level change for all these scenarios (Figure 5-21), thus the absolute location of the sediment sorting characteristics is the same for all these scenarios.

E.E. Sirks

Master of Science Thesis
Figure 5-21: Sediment distribution after one month simulation, related to sedimentation and erosion, for different initial sediment compositions. (S1: Sand Motor sediment, S2: Larger $c_u$, S3: Larger $D_{50}$, S4: Smaller $D_{50}$)

Although the sediment sorting pattern is the same, the quantitative sediment sorting is different over the profile for the different initial sediment compositions:

- A larger uniformity coefficient leads to larger extreme values of the median grain size as was expected. The maximum median grain size of scenario S2 is larger than the maximum median grain size of scenario S1, and the minimum median grain size of scenario S2 is smaller than the minimum median grain size of scenario S2. The maximum difference between the maxima is larger (about 100 $\mu m$) than the difference between these minima (about 30 $\mu m$).

- Initial sediment compositions with the same uniformity coefficient but different median grain size have the same trend in the profile, except for finer material in the erosion zone. The median grain size of the scenarios with deviations in the median grain size (S3 and S4) is almost an ‘offset’ of the sediment distribution of scenario S1, though in the erosion zone (2000 to 2300m of the offshore boundary) the median grain size of the scenario with a smaller median grain size deviates to smaller values of the median grain size.

- The most sediment sorting occurs in the ‘gentle reshaped part’ of the transect. The uniformity coefficient in this part of the profile is approximately 2 for the three scenarios with the same initial uniformity coefficient (S1, S3, S4).

5-6-3 Influence of hydraulic conditions on the sediment distribution

The hydraulic conditions that are varied in the different scenarios are the wave conditions and the water level variations. The variations in water level are varied simultaneously with the wave conditions because the same time period of measurement data is used. However the time periods are chosen based on the wave characteristics as the wave conditions are expected to have more influence on the sediment transport than the water level variations.
An other hydraulic condition that can influence the sediment distribution is the alongshore tidal current. The tidal current at the location of the Sand Motor is included in the Neumann boundary conditions at the lateral boundaries of the model as explained in Section 5-3-5.

First, the differences are researched in effect of storm and calm wave conditions on the sediment distribution. Secondly, the development of the sediment composition at different locations is analysed, related to the hydraulic conditions. Finally, special attention is paid to the development of the location and value of the minimum median grain size in the profile, related to the wave conditions.

**Influence of different wave conditions on the sediment distribution**

Four scenarios with different wave conditions are compared to research the effect of wave conditions on the sediment distribution, see Table 5-7. The first two wave scenarios are based on measured conditions and the last two are constant wave heights. The odd scenarios can be compared as high energy wave or storm conditions and the even scenarios can be compared as low energy wave or calm conditions.

<table>
<thead>
<tr>
<th>Run</th>
<th>Wave Conditions</th>
<th>Bathymetry</th>
<th>Sediment composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>Dec-11</td>
<td>Aug-11</td>
<td>Aug-11</td>
</tr>
<tr>
<td>W2</td>
<td>Aug-12</td>
<td>Aug-11</td>
<td>Aug-11</td>
</tr>
<tr>
<td>W3</td>
<td>Hs = 3 m</td>
<td>Aug-11</td>
<td>Aug-11</td>
</tr>
<tr>
<td>W4</td>
<td>Hs = 0.5 m</td>
<td>Aug-11</td>
<td>Aug-11</td>
</tr>
<tr>
<td>W5</td>
<td>Dec-11 + Aug-12</td>
<td>Aug-11</td>
<td>Aug-11</td>
</tr>
<tr>
<td>W6</td>
<td>Aug-12 + Dec-11</td>
<td>Aug-11</td>
<td>Aug-11</td>
</tr>
</tbody>
</table>

The storm wave conditions and the calm wave conditions will lead to differences in erosion and sedimentation within the profile, changing the hydrodynamics and having influence on the sediment distribution.

The large differences in bed level change after a month of simulation of the modelled scenarios is depicted in Figures 5-22 and 5-23. Apart from the large differences between the initial bed level and the bed level after the simulation time there are also differences in the median grain size after the simulation time (a month). The median grain size of the storm scenarios (W1 and W3) is large over a larger area of the transect (about 500 m), while the extent of this area is smaller (about 150 m) in the calm scenarios (W2 and W4). The maximum median grain size value in all scenarios is approximately equal, while the minimum medium grain size is smaller in scenario W2 (and W4) by about 30 $\mu m$. These observations could be caused by the stirring of the sediment by the larger waves, causing more and especially smaller sized grain size particles to be in suspension.

The most sorting takes place in the scenarios with high waves (W1 and W3), as the uniformity coefficient in these scenarios is lower than during the calmer scenarios. In storm conditions the sediment is well sorted at the location of the minimum $D_{50}$, while the sediment is poorly sorted at this type of location in the runs with calm conditions. In both cases the minimum
grain size is most likely related to the deposition of fine sediment. An explanation of the difference in (relative) magnitude of the uniformity coefficient could be sought in the type of material that is deposited. From the definition of \( c_u \) (Equation 2-1) it follows that the uniformity coefficient increases when sediment fractions with a size between the original \( D_{10} \) and \( D_{60} \) values is deposited. The uniformity coefficient decreases when sediment finer than the original \( D_{10} \), or coarser than the original \( D_{60} \) is deposited.

Development of sediment sorting at specific locations due to wave height

The scenario with varying high wave heights (W1) is used to look into the development of the sediment sorting in time, related to the wave height. As this scenario has varying wave conditions with extreme events and calmer periods this scenario can be used to research the influence of the wave height on the sediment sorting.
A few locations are selected to research the development of the sediment sorting in more detail. The locations in the profile are roughly located at the edge of the sedimentation zone, in the sedimentation zone, in the erosion zone and at the edge of the erosion zone (from left to right in Figure 5-24). The development of the median grain size in different parts of the profile responds differently to high wave heights (extreme events) and relatively calm periods. In Figure 5-25 the development in time at the above mentioned locations is plotted in time, together with the significant wave height. Based on this graph the following observations are made:

- The wave height influences the more offshore located areas of the transect only in case of extreme wave heights (1700 m and less distance to offshore start of model). In these cases the median grain size is negatively correlated with the wave height, the \( D_{50} \) decreases for wave heights of 3.7 m or higher (see Figure 5-25). The decrease in the median grain size is probably caused by the deposition of fine material that is eroded away during storm conditions and transported offshore by the undertow. This undertow and transport mechanism is also present during lower wave conditions, but with lower waves the undertow is less strong and will not reach the deeper parts of the profile.

- The median grain size at locations in the sedimentation zone of the profile (e.g. 1850 m) is positively correlated with the wave height for extreme events. In periods with lower waves the grain size decreases slowly.

- At locations in the erosion zone of the profile (e.g. like 2150m) the median grain size is correlated negatively with the wave height. Furthermore, the median grain size appears to be influenced by the water level variations as well, as the period of the water level variations (tide) is visible in the variation of the grain size.

- For locations located in the swash zone the influence of wave heights is great as only large waves (combined with high water levels) will cause flooding of the location and thus can change the sediment composition. When the location is located above water no transport takes place in the numerical model, though in practice there could be...
transport by wind. The influence of once in a while floods is visible for location 2300m in Figure 5-25, where the grain size is higher after deposition of large grains in the storm at December 8, and hereafter the grain size decreases every time a wave reaches this part of the profile.

**Location of minimum median grain size related to wave height**

A location of special interest is the location of the minimum median grain size, that changes in time. In the measurement campaigns a minimum median grain size was found around a depth of -5 to -6 m NAP. A minimum in median grain size is also found in the model results. In this section the change of the minimum value and the location of the minimum are researched, for storm wave conditions and calm wave conditions (Figure series 5-26).

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**Figure 5-26:** Development of value and position of minimum median grain size, related to wave conditions

The wave conditions of scenario W5 are a month of high waves with a few extreme wave heights and afterwards a month of calm conditions. These wave conditions in reverse order are the wave conditions of scenario W6. The following observations are made based on the figures presenting the development of the minimum grain size and its position in the profile:

- Wave conditions influence the position of the minimum median grain size in the profile. High wave conditions move the minimum median grain size offshore and during calm
wave conditions the location of the minimum median grain size is about constant, or it slowly moves shoreward. The location of the minimum $D_{50}$ moves about $200\text{m}$ offshore in the timespan of one month of storm conditions. A period of calm waves does not lead to this big changes in the location of the minimum $D_{50}$.

- When the location of the minimum $D_{50}$ has crossed a certain point in the profile, calmer wave conditions can not move the location of this minimum $D_{50}$ shoreward again (scenario W5). It is expected that the calm conditions cannot influence the location of the minimum $D_{50}$ anymore when the minimum is located outside the active zone (during the calm conditions). At a more shoreward location a ‘new’ minimum $D_{50}$ will be created, but that is not visible in this plot as it only shows the location and values of the absolute minimum median grain size.

- Storm wave conditions and calm wave conditions have a different effect on the value of the minimum $D_{50}$. High wave conditions increase the value of the minimum $D_{50}$. Calm wave conditions decrease the value of the minimum $D_{50}$, when the minimum $D_{50}$ is located within the active profile (scenario W6). When the profile is recovering from storms the $D_{50}$ at the location of the storm profile will increase.

5-6-4 Timescale of sediment sorting

The time scale of the developments of the sediment distribution in the profile related to wave conditions is researched for (1) the initial sorting, (2) extreme events and (3) the recovery of the profile. The sediment distribution in the profile at two or more moments in time is compared to asses the development for these three specific periods.

For (1) the time it takes to set the sediment sorting of the profile starting from a uniform distribution is researched for a constant high wave condition and constant low wave condition (scenarios W3 and W4). The difference between the sediment composition before, during and after a time with extreme wave heights is researched using the extreme events in the storm wave scenario (scenario W1), for (2). To research (3) the measured calm conditions are preceded by a month of the measured storm wave conditions (scenario W6).
Initial sorting of nourishment

The time scale to change the initial uniform sediment distribution to a natural distribution is researched using the scenarios with a constant wave height.

In case of a constant high wave height of 3m (scenario W3, Figure 5-27) the grain size distribution is not yet in or near an equilibrium after one month of simulation. This is probably because the bed level is not constant and the erosion and sedimentation of grains causes changes in the sediment distribution: the sediment composition becomes coarser in the eroding part of the profile and in the near shore part of the sedimentation area of the profile.

For the case with a constant low wave height of 0.5m (scenario W4, Figure 5-27) the sediment sorting appears to reach an equilibrium after one month. The bed level changes are almost zero and therefore the sediment composition does not change much.

From these observations it appears that the timescale of sediment sorting of an initially uniform profile is about a month for (constant) calm wave conditions and this timescale is larger for higher (constant) wave conditions.

![Diagram](image)

**Scenario W3.** $H_s = 3m$

**Scenario W4.** $H_s = 0.5m$

Figure 5-27: Development of median grain size in the profile, for different constant wave conditions. The moments in time are ascending with a quarter of a month ($t_0 =$ start of simulation, $t_1 =$ one month, end of simulation)

Change of sediment distribution due to extreme events

The influence of extreme events on the sediment sorting and the time scale of these processes is researched for a few extreme wave heights within the measured storm scenario (scenario W1). The effects of the wave height on the sediment distribution are presented in Section 5-6-3, this section focusses on the time scale of developments of the sediment distribution.
The sediment composition before, during and after extreme events is analysed with the sediment distribution in the profile at those moments. Figure 5-28 shows the sediment distribution development for an extreme event, the bed level change and the wave series of this simulation (W1) and where the ‘snapshot’ moments are within the simulation time. This figure is representative for the development of the sediment distribution around the other peaks in this simulation as well.

- The sediment distribution at the extreme event shows an overall high median grain size in the area directly affected by the wave action. Both before and after the extreme event the median grain sizes are smaller. It is expected that fine material is in suspension during high wave conditions.

The timescale of bringing material into suspension during high energetic wave conditions is small. The time period between consecutive ‘measurement points’ of the model results is short, ranging from 9 to 50 hours, but the sediment composition reacts quickly to the wave conditions, as the difference in median grain size is even 30 µm in a time period of 9 hours (Figure 5-28).
The critical shear stresses are exceeded and the material is brought into suspension directly. This is a quick reaction to the forces applied to the grains. During milder wave conditions the critical shear stresses of some of the grains will be exceeded but not of all grain sizes. During milder wave conditions particles might also settle, while during extreme events sediment will not be able to settle.

- Extreme events influence the settlement of fine material further offshore positively. From Figure 5-26 it was already observed that extreme events move the position of the minimum median grain size further offshore. The movement of the minimum median grain size in offshore direction is also visible in Figure 5-28. The timescale of the movement of this minimum coincides with the timescale of the extreme event. In between extreme events the position of this minimum is fairly constant or the minimum moves slowly in direction of the shore.

- The timescale of changes in sediment sorting without extreme events but with considerable waves (up to 3.7m, with an average of 1.1m) is 10 times as long for the same changes in sediment sorting. These values originate from the comparison of the sediment sorting at and after the first extreme wave event in scenario W5 (t_2 and t_3 respectively in Figure 5-29 ‘Extreme events’) and from approximately this moment in time to a quarter of a month later (t_1 and t_2 in Figure 5-29 ‘Milder conditions’).
Figure 5-29: Comparison of development in sediment distribution in the profile by an extreme event and by milder conditions.
Recovery of the sediment distribution

The time scale to recover a sediment distribution after an extreme event is researched. The results of the model run with a month of extreme conditions followed by a month of calm conditions is analysed and compared to the model run of a month of calm conditions that is not preceded by storm conditions.

During the recovery period the morphologically active profile is smaller than during the preceding storm wave conditions, based on the formulations of the closure depth. After half a month even barely any sedimentation or erosion occurs. This is comparable to the situation of calm wave conditions on the initial profile (scenario W2, Figure 5-22).

The effect on the grain size distribution in the profile is the creation of a new minimum in the median at the offshore boundary of the active profile (Figure 5-30). This new location of the minimum grain size is expected to be created by deposition of sediment, this is not transported much further than the active profile, thus a new minimum is created and the old minimum stays constant. However, about 250m offshore of the edge of the (morphologically)
active profile the median grain size changes to a finer sediment, closer to the original sediment composition (Figure 5-30). The above observations lead to the conclusion that the old profile can not be fully recovered. A time scale for a full recovery process thus not exists, though the time scale of the constitution of the sediment sorting belonging to calm conditions can be researched.

5-6-5 Comparison with measurement data

The model results are compared with measurement data to see whether the model results are qualitatively comparable with the measurement results. When the model results show the same patterns as the measurement data this could be an indication of the model to take the relevant transport processes into account. Limitations of the model make it impossible to compare the model results with the measurement results in a quantitative way, though this is not important as this was not the goal of the use of model simulations. These limitations are discussed extensively in the section dedicated to the limitations of the use of a 2Dv model in this case and the discussion section of this chapter (Sections 5-4 and 5-7).

The model results are compared with the measurement data using the analysis of the model results from Section 5-6-1 on the characteristic sediment sorting pattern related to the sedimentation and erosion in the profile. The model results of scenarios C1 and C2 and the grain size parameters measured at T3 are plotted against the sedimentation/erosion within the transect in Figure 5-31. The sedimentation erosion of the profile in February 2013 is the bed level change of 6 months, determined based on the bathymetric data of Shore monitoring and JARKUS data. A few remarks have to be made on this approach to compare the model outcome with the measurements:

- The bed level change of the Sand Motor situation during the T3 measurement campaign is negative (erosion) everywhere because the profile moves shoreward in time because of the structural erosion. Scenario C1 with morphological updating shows both sedimentation and erosion as the Sand Motor model does not model structural erosion. The comparison of the grain size parameters with sedimentation and erosion would thus undoubtedly result in different characteristics.

- Furthermore, the variations in the sedimentation and erosion rates in a real profile are less straightforward than the model represents the development of cross-shore morphology like bars (see Section 5-4). The measured variations in grain size parameters can be related to these morphologic features, where the model results lack this influence.

From the above it can be concluded that it is difficult to compare the model outcome with the measurements based on the bed level change in the profile.

A first primitive solution to be able to compare the measured sedimentation and erosion pattern with the modelled sedimentation and erosion pattern would be to shift the measured bed level change offshore to match the location of the profile in the model. To better match the sedimentation erosion pattern of the model the measured bed level change would also have to be translated in such a way that there is no structural erosion (or accretion) in the profile. If the profile is shifted and translated the position of the minimum median grain size
would approximate the position of the minimum median grain size from the model results of scenario C1.

From the above observations on the comparison of the model outcome with the measurements, the most important findings are:

- The model reproduces the general trend in grain size of coarse sediment nearshore decreasing to a absolute minimum median grain size. The location of the minimum median grain size in the model approximates the location found in the measurements.

- The model does not reproduce the coarsening of the sediment composition offshore of the location of the minimum median grain size. In measurements the sediment around the depth contours of 8–10 m is significantly coarser than the average sediment in the transect (also in other transects at the Sand Motor in T2 and T3 campaigns, see Figure 4-27).

The differences between the model results and the measurement data could be caused by the lack of structural erosion in the Delft3D model, the fact that the hiding and exposure parameter is not included in the transport formulation, or the model results could be biased at this location or contain other errors:

- Structural erosion would expose ‘Sand Motor’ sediment in the nearshore zone especially with an average median grain size of 278 $\mu$m. This sediment is visible in the model results (Figures 5-31 and 4-27) and creates a local minimum in grain size nearshore as the Sand Motor sediment is finer than the average sediment diameter at this location. The average sediment composition in the transect is coarser probably due to the local contraction of the tidal currents because of the Sand Motor. Delft3D models erosion reshaping the original bathymetry to a profile with a more gentle slope. Though this erosion process does not lead to a relatively fine sediment composition nearshore.
• The structural erosion of sediment of the profile could lead to relatively more transport of coarser sediment than Delft3D models without the structural erosion. It is expected that more coarse sediment is transported in a period of structural erosion than with a constant shoreline. When the profile erodes structurally all the sediment has to be transported. The finer sediment fractions might be transported especially alongshore and be partially deposited North of the Sand Motor. The coarser sediments might be transported by the undertow especially in high energy wave conditions and deposited in the deeper part of the profile. As Delft3D does not model the structural erosion there is less coarse material to be transported.

• A deficiency in the transport of coarser sediment (in offshore direction) could be caused by the lack of the incorporation of a Hiding and Exposure parameter in the transport formulation. Larger grains will be more easily transported in an armoured layer and this is not taken into account in the transport calculation in the model.

• Apart from the limitations of the 2Dv model, the measurement results could contain errors and not be a good representation of the sediment composition. A possible bias could be the presence of fine sediment clogging together and resulting in a positive bias of the nominal grain sizes.

5-6-6 Sensitivity of model to model parameters

The sensitivity of the model is researched for the model parameters of the bed gradient factors for bed load transport and the thickness of the underlayer and transport layer. The results of the runs with variation in these parameters leads to conclusions on the sensitivity of the model to these parameters.

![Figure 5-32: Sensitivity of model for different values of parameters α_{bs} and α_{bn}](image)

The default values for the α_{bs} and α_{bn} parameters result in instability in the morphodynamics of the model, see Figure 5-32. Higher values for α_{bs} and α_{bn} have stable results, within this simulation period of one month at least. The effect of these parameters is the largest in the
swash zone, which is understandable as a large portion of the sediment transport in this region will be bed load transport. In the rest of the profile the differences between the stable runs with different values for the $\alpha_{bs}$ and $\alpha_{bn}$ parameters are smaller than 10 $\mu$m and the trend is the same.

The numerical model is not sensitive at all to a change of the underlayer thickness (Figure 5-33), as there is no or barely variation between accretion and sedimentation per location this has no influence on the grain size parameters. The thickness of the transport layer influences the resulting grain size parameters, see Figure 5-34. Though when a reasonable size of transport layer is chosen (not too large or too small) the absolute difference in the grain size parameters are not big and the overall trend is the same.

5-7 Discussion

This section discusses (1) the consequences of 2Dv model limitations (2) the influence of model parameters on the model results and (3) the use of the bed level change to relate the sediment distribution to.

Model performance

Limitations of the use of a 2Dv model

The morphologic behaviour of the cross-shore transect is not representative of the morphologic behaviour at the Sand Motor, as it lacks bar-trough morphology development in the profile and structural erosion of the profile. However, the cross-shore model is aimed to research the effect of wave forcing and initial conditions on the sediment sorting processes. As the model simulates the wave action and the sedimentation and erosion of the profile (without
small scale features like bars and without structural erosion), the sediment sorting related to 
sedimentation and erosion can be researched.

**Validation of model**
The lack of the modelling of morphologic processes has as a consequence that the model cannot 
be calibrated and validated based on the modelled bathymetry. No calibration is executed 
on the model based on the model results, so the model results can only be interpreted as 
qualitative results.

**Sensitivity of model**
The model is shown to be barely sensitive to a variation of the model parameters of the bed 
gradient factors for bed load transport and the thicknesses of the underlayer and the transport 
layer. The bed gradient factors for bed load transport cause the largest differences and those 
are smaller than 10 $\mu$m. The different model parameters did not change the overall trend. 
The small influence of these model parameters means that the model is robust. However, 
there are many more model parameters in Delft3D that were not researched and that could 
have a large influence on the sediment distribution in the profile.

**Influence of model parameters**

**Influence of used sediment fractions**
The influence of the size of the largest sediment fraction proved to be of mayor influence 
for the maximum median grain size in the profile. This resulted from different combinations 
of sediment fractions for the representation of the sediment composition of the Sand Motor 
sediment. As the sediment composition itself was not changed, the sediment sorting in the 
profile should not have changed either. The model behaviour has to be understood in order 
to be able to interpret the input and output correctly, therefore it is recommended to research 
the effect of the change of the sediment fractions.

**Influence of the lack of a Hiding and Exposure parameter**
A parameter for the Hiding and Exposure of grains was not used in the model, as the used 
transport formula of Van Rijn (2004) does not include the possibility to include this parameter. 
As explained in Section 2-2-1 the presence of multiple sediment fractions in the bed can lead to 
armouring of the bed and influence the critical shear stress for initiation of motion for hidden 
and exposed grains differently. The lack of a Hiding and Exposure parameter in the model 
simulation overestimates the transport of fine material and underestimates the transport of 
coarse material in case of an armoured bed. An armoured bed will typically be formed at 
locations where the bed is eroding.

**Influence of the initial sediment composition on sediment transport**
In the results of one month of simulation of storm conditions on the same bathymetry with 
different initial sediment compositions the bed level change was almost identical, though there 
were difference in the sediment distribution. This result does not match with the expectation 
based on theory that the grain size influences the sediment transport. The sediment transport 
formula of Van Rijn (2004) is dependent on the sediment grain size and would thus result in 
different transport rates for different sediment compositions. It is recommended to look into 
the cause of this unexpected model behaviour.
Use of cumulative bed level change to relate to the sediment distribution

Some remarks have to be made on the use of the cumulative sedimentation and erosion in the profile to relate the sediment sorting patterns to.

- The model considers the sediment mixture of the transport layer, the upper 10cm, as the sediment composition. Though the implicit assumption is made in the model analysis that the total sedimentation and erosion pattern influences the sediment sorting. It is of importance whether the area was accreting or eroding in the time period during which the toplayer of sediment was deposited and what the (wave) conditions were during the sedimentation. In the case of the results of the modelled scenarios considering only the last 10 cm of accretion at every location would make a difference especially in case of varying wave conditions, as the areas of sedimentation and erosion are then shifting in the profile.

- The time period over which the bed level change is calculated influences the amount of sedimentation and erosion, and in case of different wave conditions, also the pattern of sedimentation and erosion in the profile.

In the model runs of one month the sedimentation and erosion pattern at the end of the simulation is calculated as the total bed level change in the runtime of the model. In the model runs that evaluate the timescales of different processes the sedimentation and erosion pattern is calculated based on the bed level difference of the current and the preceding analysed moment in time, with time periods of around a week. The effect of the length of the considered time period is expected to be especially large when considering variable wave conditions or a period of calm waves after a period of high waves. In both conditions the influence of high energy wave conditions will (still) be the most important influencer in the sedimentation and erosion pattern although the current (calmer) wave conditions will have influenced the sediment composition in the near shore part.

- The use of the sedimentation and erosion pattern to relate to the sediment sorting is not of much use in the case of calm conditions as in calm conditions the bed level change is almost negligible. However without (much) bed level change sediment sorting does take place, both in the initialisation period as in a recovery period, and can not be related to the sedimentation and erosion pattern as this is non existent.

Based on the above discussion evaluation is needed on whether the bed level change can be used to relate to the sediment sorting and what timescale is needed to evaluate the sediment sorting based on the sedimentation and erosion pattern.

5-8 Conclusions

A cross-shore model was set-up in Delft3D to simulate the sediment sorting processes in the cross-shore direction at the Sand Motor. Different scenarios were simulated to research the effect of different parameters on the sediment distribution and the time scales of the sorting processes. From the analysis of the model results the following conclusions are drawn:
• The sediment sorting processes in a profile can be reproduced qualitatively by a 2Dv model in Delft3D.

The general trend in the median grain size in the profile is the same, as the median grain size nearshore is relatively large and the median grain size decreases in offshore direction to a minimum medium grain size.

The location of the minimum median grain size in the model appears to behave coherent to the observation of the measurement data: the summer season with lower wave conditions creates a minimum median grain size more nearshore than the higher wave conditions in winter.

The model does not reproduce the coarsening of the sediment composition offshore of the location of the minimum median grain size. This could be caused by the lack of structural erosion in the 2Dv model, the miss of a hiding and exposure parameter in the transport formulation or by measurement errors.

• The sediment sorting processes at a transect at the Sand Motor can not be reproduced quantitatively by a 2Dv model in Delft3D.

The model results do not match with the measurement data quantitatively. The values of the maximum and minimum median grain sizes and the location of the minimum median grain size differ. It is expected that this is partially caused by the limitations of the model set-up that can not model the structural erosion present at the Sand Motor, does not model bar behaviour correctly and does not have a hiding and exposure parameter in the transport formulation. These limitations of the model cause deviations in the sediment sorting of the model compared to the reality as the sedimentation and erosion patterns are different.

• The sediment sorting in the profile is strongly influenced by the sedimentation and erosion patterns.

The following characteristics were found during relatively calm conditions after extreme wave heights:

- A local minimum in the median grain size is located at the turning point of erosion and sedimentation.
- The absolute minimum median grain size is located just offshore of where the profile accretes.
- An offshore situated local maximum of median grain size is located at the location of maximum sedimentation.
- Larger than average median grain sizes are found in the area of the profile where the original slope is reworked to a more gentle slope.

• The sediment sorting pattern is independent of the initial bathymetry and initial sediment composition.

The same characteristic sorting pattern was found after the same wave conditions for different initial slopes of the nourishment and different initial sediment compositions.

• The sediment distribution is dependent on the initial sediment composition.

The initial sediment composition of the nourishment influences the median grain size within the profile proportionally when the uniformity coefficient is the same. A different uniformity coefficient of the sediment composition influences the gradients in the sedi-
ment grain size, with a larger uniformity coefficient causing larger differences in grain size.

- **Wave conditions influence the area where sediment sorting takes place.**
  The wave height determines the offshore boundary where sediment sorting takes place in the profile. This boundary appears to be just offshore the location of the closure depth (also depending on the wave height), the offshore boundary of the morphologically active profile. Consequently, the wave height determines the location of the absolute minimum median grain size, as this location is correlated to the offshore boundary of the active profile according to the sediment sorting pattern. Higher wave heights thus influence the sediment composition in a larger area in the profile than calm conditions, creating a minimum in the median grain size more offshore or nearshore respectively. As calm conditions can not influence the deep part of a profile a minimum median grain size created by high wave heights can not be changed by calm conditions.

- **The sediment composition is well sorted at the location of the minimum median grain size during storm conditions.**
  During storm conditions the uniformity coefficient has a minimum at the location of the minimum median grain size. It is expected that the deposition of fine sediment causes this minimum. In this case the deposited sediment fractions will mainly be sized between the $D_{10}$ and $D_{60}$ values as this decreases the uniformity coefficient by definition.

- **Wave conditions influence the timescale of sediment sorting.**
  The wave height is responsible for the timescale of changes in the sediment distribution. The sediment distribution responds almost instantaneously to extreme events, whereas lower wave conditions take more time to realise the same amount of change in the sediment composition.
The research questions from the introduction chapter are answered in here based on the information in this thesis, especially Chapters 4 and 5. Recommendations for further research are given in Chapter 7.

**Sediment sorting in the Sand Motor area**

The sediment distribution in the Sand Motor area was researched to find out how the nourished sediment is sorted at and around the Sand Motor. The development of the sediment sorting at a nourishment the scale of the Sand Motor had not been researched before. The data on sediment sorting at the Sand Motor is used to formulate hypotheses on the sediment transport processes at nourishments.

The measurement results of 3 measurement campaigns were used. The data consisted of the measured sediment composition of sediment samples taken in the Sand Motor area. One measurement campaign was performed before the construction of the Sand Motor and was considered to represent the natural undisturbed situation. The two last data sets were obtained after the construction of the Sand Motor. These data sets were used to research the development of the sediment distribution at this location and the influence of the Sand Motor on the area North of the Sand Motor.

1. **The sediment composition in the area of the Sand Motor was coarser after construction.**
   At other large scale nourishments where coarser sediment than the native material is used to construct the nourishment the same result can be expected.

2. **The longshore sediment sorting has increased in the period after the construction of the Sand Motor.**
   The median grain size at the Sand Motor is about 100 $\mu m$ larger than the median grain size North of the Sand Motor. The shape of the Sand Motor is expected to have caused an increased erosion of fine material at the Sand Motor and deposition of this fine material North of the Sand Motor.
At the Sand Motor the sediment composition has become more sorted in time. The uniformity coefficient of the Sand Motor transects was measured to be between 1.5 and 2 compared to values between 2 and 2.5 in the situation before the construction of the Sand Motor. This matches the hypothesis that especially finer sediments are eroded at the Sand Motor.

The sediment sorting in the cross-shore direction has a minimum median grain size that moves offshore during high wave conditions. It is assumed that the wave conditions preceding the measurements have influenced the location of the minimum median grain size.

The Sand Motor influences the cross-shore sediment sorting. The sediment sorting pattern in the Sand Motor transects and the transects North of the Sand Motor was different, although before the construction of the Sand Motor the cross-shore sediment sorting in these areas was comparable.

Influence of environmental parameters on the sediment sorting process and timescale

The numerical model Delft3D was used to research the sediment sorting processes and timescales in the cross-shore direction at a large scale nourishment. The bed stratigraphy module of Delft3D was used to track the development of sediment sorting in several layers. Although the 2Dv model has limitations concerning the correct representation of morphology it can be used to model the qualitative sediment sorting behaviour. The influence of the bathymetry, sediment composition and wave conditions on the sediment sorting process and time scale was researched by variation of these parameters in dedicated model runs. The hypothesis that the minimum median grain size in the cross-shore direction is dependent on the wave height was tested with the model.

The sediment sorting process in the profile is strongly influenced by the sedimentation and erosion patterns. A characteristic sediment sorting pattern was found during relatively calm conditions after extreme wave heights. This sorting pattern showed a relationship between the sediment sorting and the bed level change.

The sediment sorting pattern is independent of the initial bathymetry and initial sediment composition. The same characteristic sorting pattern was found after the same wave conditions for different initial slopes of the nourishment and different initial sediment compositions.

Wave conditions influence the area where sediment sorting takes place. The wave height determines the offshore boundary where sediment sorting takes place in the profile. Higher wave heights thus influence the sediment composition in a larger area in the profile than calm conditions.

Wave conditions influence the timescale of sediment sorting. The sediment distribution responds almost instantaneously to extreme events, whereas lower wave conditions take more time to realise the same amount of change in the sediment composition.
The location of the minimum median grain size in the profile is related to the wave height. Higher wave heights move the minimum median grain size offshore, whereas calm wave heights cannot influence this deeper part of the profile and create a minimum located closer to the shore. The location of this minimum is found to be located at the edge of the morphologically active profile and is thus related to the wave height via the closure depth formulation. This confirms the hypothesis formulated on basis of the measurements that the location of the minimum median grain size in the profile is dependent on the wave conditions.
Chapter 7

Recommendations

Based on the findings of the performed research a number of recommendations are made to (1) improve the set-up of the measurement campaign of the sediment composition in the Sand Motor area, (2) improve the current cross-shore model in Delft3D and (3) evaluate the current interpretation of the model results. Furthermore recommendations are made on (4) how to test the hypotheses that were made but not tested in this thesis. And finally, some research into (5) other factors that possibly influence the sediment sorting is recommended.

Improvement of the set-up of the measurement campaign

- It is recommended to perform sediment composition measurements twice a year at the Sand Motor to be able to study the influence of extreme events and the development of the sediment composition. One measurement campaign should take place just after an extreme wave event and one at the end of the summer period.
  A measurement campaign just after an extreme event will make it possible to relate the measured sediment distribution to the wave conditions of the extreme event, as the sediment distribution was found to be most dependent and quickly responding to high wave conditions.
  A measurement campaign in the end of the summer period would be the best option to study the long term development of the sediment distribution in the area. As a long period of low wave heights will have restored the influence of the storm season and the independent extreme events in the nearshore zone and the calm wave conditions do not influence the sediment composition in the deeper part of the profile.

- It is recommended to increase the number of sediment samples analysed per measurement location as the standard deviation per measurement location can be higher than the measured variation between measurement points in a profile. More samples at less locations is preferred above sampling at more locations, as more samples decrease the presence of random measurement errors in the laborious measurement process.
  With the knowledge of this research the number of measurement locations could be brought down to keep the number of total samples constant. It is recommended to
sample at least a transect at the Sand Motor and two transects North of the Sand Motor to be able to research the cross-shore transport processes at the Sand Motor and the development of the area of fine material in the longshore direction.

- It is recommended to make notes on the estimated thickness of the sediment that is sampled with the Van Veen grab sampler, as the measured sediment composition corresponds to that layer thickness and the sample thicknesses could well differ and thus influence the measurements.

- Regarding the sieving analysis and the data processing, it is recommended:
  - ...to do more tests to determine the reproducibility of the sieve analysis. More tests on different type of samples will improve the estimation on the reproducibility of the sieving method.
  - ...to remove shell fragments from the sediment samples before to improve the results of the sieving analysis. The removal of shell fragments makes sure that the differences in the sediment composition is measured instead of also measuring the differences in the shell content.
  - ...to use the wet sieving method on sediment samples sampled at a water depth larger than 8 m (- NAP) and in areas where the sediment composition can be expected to be fine, like North of the Sand Motor. The application of the wet sieving method will prevent the clogging of fine material and will better represent the sediment composition.
  - ...to improve the linear approximation of the measured sieve curve to a curve to improve the accuracy of the nominal grain sizes obtained from the sieve curve.

**Improvement of the cross-shore model in Delft3D**

- It is recommended to test the influence of the inclusion of a hiding and exposure factor for the sediment transport. It is expected that the inclusion of a hiding and exposure factor for the sediment transport influences the sediment distribution significantly. This hypothesis can be tested with a transport formula that includes a hiding and exposure parameter like the Meyer-Peter Müller transport formula. When this hypothesis is confirmed, it is recommended to use a transport formula that takes hiding and exposure of grains into account when modelling the sediment transport of a sediment with multiple sediment fractions. Either the current transport formula of Van Rijn (2004) has to be adjusted to use a hiding an exposure parameter or a sediment transport formula that includes a hiding and exposure parameter has to be used.

- It is recommended to try to calibrate the parameters that influence the possible bar formation (e.g. the wave-related bed load and suspended load factors, BedW and SusW) to see if it is possible to get the breaker bar formation in the model to improve the representation of the morphology.

- It is recommended to research the sensitivity of the model for model parameters besides the ones already tested in this research.

- It is recommended to research the effect of the input of the range of the sediment fractions in the model on the modelled sediment distribution. As the cause for the found
deviations in the output of the sediment composition when using different sediment fractions is not known.

- It is recommended to research the influence of the grain size on the sediment transport in Delft3D using the Van Rijn (2004) formula. In the model simulations the bed level change with a different sediment composition lead to almost identical bed level changes. This was not expected as the sediment transport depends on the grain size so it is recommended to look into the cause of this unexpected behaviour.

Evaluate the interpretation of the model results

- It is recommended to evaluate the use of the bed level change to relate to the sediment sorting and what time scale is needed to evaluate the sediment sorting based on the sedimentation and erosion pattern.

- It is recommended to research for what type of wave conditions the found sediment sorting pattern related to the sedimentation and erosion applies.

Test hypotheses that were not tested in this research

- It is recommended to test the hypothesis that finer sediment fractions are transported offshore during high energy wave conditions and are not transported shoreward again or can not settle near shore anymore. This hypothesis can be tested in Delft3D by using sediment fractions with the same sediment characteristics but a different name. The displacements of these sediment fractions can be tracked down more easily.

- It is recommended to research the cause of the difference in the sediment sorting pattern at the Sand Motor at a water depth of 8–10 m (- NAP). The possible explanations are the lack of structural erosion in the model, the lack of a hiding and exposure parameter in the transport formula of the model, or measurement errors.

- The hypothesis on the cause of the increased alongshore sediment sorting can be researched with a 2Dh model of the Sand Motor area. It was hypothesised that the wave focussing and the contraction of the alongshore current at the Sand Motor are both causing the increased alongshore sediment transport of relatively fine sediment of the Sand Motor to North of the Sand Motor. A 2Dh model of the Sand Motor could provide insight in the relative importance of those mechanisms on the sediment sorting.

Research other factors influencing the sediment composition

- Local morphologic features as breaker bars were not modelled and the effect of these features on the measured sediment composition was not researched. Though it would be interesting to see the effect of local morphologic features such as bars on the sediment sorting in the cross-shore direction. The use of a model set-up that can model morphologic bar-behaviour is recommended over taking measurements at the exact location of a bar, as the last is proven difficult even with excellent sailing skills. The model results can be visualised in the cross-shore direction together with the bathymetry to analyse the effect of bars on the sediment distribution.
• The measurement results and model results can be compared to the theory of Dean (1977) on the equilibrium profile. The equilibrium profile can be calculated for the different sediment fractions and the slope of the reshaped profile can be determined from the model results or bathymetric surveys. It is recommended to divide the profile in parts corresponding to different angles and compare the grain size parameters found in these areas.

• The stratification in the water column is not taken into account, although stratification can be expected to play a role as the Sand Motor area is located in the Rhine ROFI (Region Of Freshwater Influence). Stratification can influence sediment transport as it suppresses the turbulence in the water column. It is recommended to research whether stratification contributes to the sediment sorting processes.

• The density and the shape of the grains is assumed constant in this thesis. It is recommended to research whether the density of grains and the shape of grains in the Sand Motor area differs and how these parameters would influence the sediment sorting.
A-1 Taking sediment samples with a Van Veen grab sampler

The method of taking sediment samples with the Van Veen grab sampler is presented here step-wise.

- Sailing towards the coordinates of the measurement location
- Preparing the Van Veen grab sampler for deployment
  - Clean
  - Open buckets by lever
  - Safety check for the rope and position of deployer
- Preparing sample bags for samples of measurement location
- Deploying the Van Veen grab sampler at the measurement location
  - Preventing the rope from getting too loose when the sampler hits the bottom
  - Taking a sample by pulling the rope, gently at first
  - Bring in the Van Veen grab sampler by pulling the rope, with an extra person for more speed
- Administration of location information
  - Measured depth (wave averaged)
  - Time
  - (GPS coordinates measured by hand held GPS)
- Obtaining a sediment sample from the Van Veen grab sampler
  - Opening the Van Veen grab sampler
  - Taking part of the sample with hands to put in a pre-numbered sample bag
  - Scraping out Van Veen grab sampler with a small shovel if more sediment is needed
A-2 Removal of carbonate content from sediment samples

The shell fragments consist of CaCO$_3$, a high concentration (4M) HCl in sufficient quantity was added to make sure that after a while all the carbonates have reacted with the HCl and a salt (CaCl$_2$) was formed, soluble in water. Expressed in a scientific formula in A-1. To accelerate the reaction process the mixture was heated and stirred constantly for 30 minutes. The end of the reaction process was visible because no visible reaction took place anymore. The sediment mixture was filtered through a Büchner filter under air suction and washed with water to remove the acid.

\[
CaCO_3 + 2HCl \rightarrow H_2O + CO_2 + CaCl_2 \tag{A-1}
\]

The procedure on how to remove carbonate content from a sediment sample is presented here step-wise.

Preparation of the sample:

- The sample is sieved with water, because the sample is wet
- A retaining tin is used, to contain the fine material. (Though with the decanting of water some fine material is probably also lost)
- The fraction larger than 1.18 mm is removed (large shells, stones and other)
- The sample is oven dried and weighed

Measurement equipment:
- 4M HCl
- Erlenmeyer
- ‘stopbol’ (in Dutch)
- Stir bar
- Hot plate
- Water bottle with nozzle
- pH-paper
- Büchner filter
- Filter paper
- (Air) Pump

Execution process:

- Putting sediment sample in Erlenmeyer
- Adding small amount of 4M HCl (in fume cupboard)
- Waiting till the reaction is less
- Continuing to add 4M HCl is small amounts till an amount of 100-150 ml is added. (The exact amount is not important, as long as there is enough HCl to react with all the carbonate material)
- Heating the mixture for 30 minutes on a hot plate, using the stir bar to stir the mixture and a ‘stopbol’ to create a reflux system, so the mixture does not boil dry.
- Putting the filter paper in the Büchner filter and wetting the paper to make sure it seals the holes in the Büchner filter with the paper.
- Connecting the suction-erlenmeyer with the air pump
- Filtering the mixture through the Büchner filter. Suction of the air pump a under pressure makes the filtering goes faster.
- Washing the residue with water to remove the acid
- Testing the pH value of the filtrate with pH-paper
- Washing until the pH value of the filtrate is close to neutral.
A-3  Sieving sediment samples according to British Standard sieving procedures

To determine the grain size distribution the samples are sieved using either the dry or the wet sieving method. Which method is used depends on the expected amount of fine material in the sample. The different methods are explained below.

A-3-1 Measurement set up

A set of sieves with aperture sizes ranging from 1.18 mm-63 µm is used. The largest sieve size is chosen to be 1.18 mm because the largest grain particles were expected and found in the 0.600 mm sieve and with one sieve size larger, the larger shell and stone particles can be easily filtered and taken out of account in the grain size analysis. The sieves are positioned with the largest sieve on top and a receiving pan under the smallest sieve at the bottom. The dried sample is placed on the top sieve and is shaken for an amount of time until there is no particle movement through sieves any more. The amount of time to shake the sample is based on the measurement outcome of a few samples: sieving longer than 7 minutes did not make (much) difference, so a sieving time of 7 minutes is used.

The amount of material on each sieve is put into a weighed bowl on a weighing scale, starting with the topmost sieve and writing down the cumulative weight of the sieved fractions. The material stuck in the sieve has to be brushed out of the sieve using a sieve brush, placing the sieve upside down on a sheet of paper. The mass in the receiving pan is also weighed; this is the fraction that passed the 63 µm apertures. The accuracy of the weighing device should be at least 0.1% of the total initial test sample mass.
A-3 Sieving sediment samples according to British Standard sieving procedures

Figure A-6: Sieving installation

Figure A-7: Photos of different sieve fractions: 1.18mm, 600 µm, 150 µm
A-3-2 Dry sieving method

The dry sieving method is applied for samples near the Sand Motor and near the coast, because these samples do not or barely contain fine materials. An amount of 100 to 150 g of the original sample is taken to be dried in an oven (at 105–110 °C for 24 hours) and sieved afterwards. The minimum boundary of 100 g is taken from the sieving manual, and the maximum boundary of 150 g is chosen as a practical maximum value, because with higher values the chance is higher that a sieve becomes overloaded. An overloaded sieve had more material (in g) on the sieve than the maximum amount at which it functions well. An overloaded sieve will prevent grains from passing through the sieve and result in a too high estimate of the grain size diameters.

A-3-3 Wet sieving method

The wet sieving method is applied for the samples containing fines: silt or clay, or both, even in small quantities. The dry sieving method will not work for these samples because fine particles of silt and clay can adhere to sand-size particles and will not be separated by dry sieving. If clay is present, or there are signs of particles sticking together, the material should be immersed in a dispersant solution before washing according to BS1377: Part 2: 1990 (British Standard wet sieving procedure). In the samples in this measurement campaign, no or almost no clay was present in the samples, based on visual observation of the samples. The samples were not treated with a dispersant solution before drying the samples in the oven. The dried sample is weighed. (Assuming that all particles will pass a 20mm sieve.) The 1.18 mm sieve is placed on top of the 63μm sieve, with some intermediate sieves in between to prevent overloading of the 63μm sieve, as every sieve may not contain more than 150 g at a time to let the washing function correctly. A water hose is connected to the lid, spraying water on the sieves. A different type of receiver tin is used: with a hose to drain the water and fine material. The sample is placed on the top sieve and washed, washing out the particles smaller than 63μm. This is continued until the wastewater is seen to run clear. The material contained on the sieves is collected and dried in an oven at 105–110 °C for 24 hours. The total left over sample material is weighed. The difference between the first weighing moment and the second is the weight of the fine material washed away. From this point onwards the procedure is identical to the dry sieving procedure.
Data processing methods

B-1 Determining nominal grain sizes from weight percentages

The outcome of a sieving process is the cumulative weight per sieve size. These weights are transformed to passing percentages per sieve size and via sieve curves to nominal diameters.

Absolute weight per fraction

The absolute weight retained by a sieve is the cumulative weight of that sieve minus the cumulative weight of the previous sieve (with larger apertures). Sediment sample C05-I (the first sample of measurement location C05) is used as an example:

<table>
<thead>
<tr>
<th>Sieve size [mm] / Weight [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample: C05-I Total 1.18 0.6 0.425 0.3 0.212 0.15 0.063 smaller</td>
</tr>
<tr>
<td>125.5 1.17 5.93 21.68 61.09 96.98 117.55 125.27 125.34</td>
</tr>
</tbody>
</table>

The weight retained in the sieve with size 1.18 mm is disregarded because this sieve fraction only contains shells and small stones. The total measured weight is thus adjusted for the disregarded weight in the 1.18 mm sieve. The cumulative measured weight is summed up and compared with the total weight measured before the sieving procedure (=total weight). The difference in relation to the total weight is the error percentage (in this case 0.13 %). The measured weights per sieve size can also be written as weights per sieve fractions, a range of grain size diameters.

<table>
<thead>
<tr>
<th>Sieve fraction [mm] / Weight [g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample: C05-I Total 1.18 - 0.6 0.6 - 0.425 0.425 - 0.3 0.3 - 0.212 0.212 - 0.15 0.15 - 0.063 0.063 - 0</td>
</tr>
<tr>
<td>124.33 4.76 15.75 39.41 35.89 20.57 7.72 0.07</td>
</tr>
</tbody>
</table>
Weight percentage
The absolute retained weight per sieve size is used to calculate the weight percentage of the fraction of sizes ranging from the sieve size above till the current sieve size. The percentage is the absolute weight relative to the total weight. The sum percentage plus the error percentage make 100 %, which is used as a check for correct calculation. The weight of the shells in the 1.18 mm sieve related to the total original weight represents the percentage of shells in the original sample.

Table B-3: Weight percentage per sieve size (sample C05-I)

<table>
<thead>
<tr>
<th>Sieve fraction [mm]</th>
<th>Weight Percentage [%]</th>
<th>Sum [%]</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>C05-I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.18 - 0.6</td>
<td>3.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6 - 0.425</td>
<td>12.67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.425 - 0.3</td>
<td>31.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.3 - 0.212</td>
<td>28.87</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.212 - 0.15</td>
<td>16.54</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.15 - 0.063</td>
<td>6.21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.063 - 0</td>
<td>0.06</td>
<td></td>
<td>0.13</td>
</tr>
</tbody>
</table>

The weight percentage per fraction can be visualised in a histogram, see Figure B-1. The measured weight percentages of the different fractions are depicted as bars in the middle of the grain size range that the measured grains represent.

Figure B-1: Weight percentage per sieve fraction of sample C05-I

Passing Percentage
The passing percentage of a sieve can be calculated as the passing percentage of the sieve before minus the weight percentage of that sieve. The passing percentage of the 1.18 mm sieve is 100% because the shell material retained on that sieve is ignored, so all considered material passes that sieve. In the example case of sample C05-I, the passing percentage of the 0.6 mm sieve is 100% - 3.83% = 96.17%.

This calculation procedure leads to a passing percentage with the error percentage ‘included’,

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(otherwise the 1.18mm passing percentage would not be 100%). This inclusion of the error percentage leads to the largest relative error for the fraction with the smallest passing percentage: the 0.063mm sieve. The relative error is more than 200% in this case, but the effect on the sieve curve is negligible if the error percentage is small (< 1%).

<table>
<thead>
<tr>
<th>Sieve size (mm)</th>
<th>Passing Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample:</td>
<td>1.18 0.6 0.425 0.3 0.212 0.15 0.063</td>
</tr>
<tr>
<td>C05-I</td>
<td>100 96.17 83.5 51.81 22.94 6.39 0.18</td>
</tr>
</tbody>
</table>

**Additional step for wet sieving method**

Samples sieved with the wet sieving method have an extra attribution to the smallest fraction (the retention tin: 0.063 - 0.0 (mm)) that is not measured during the sieving process. The difference between the total original weight and the weight after washing is considered to consist only of fine sediment and thus belong in this finest fraction. The total weight measured before starting the dry sieving procedure is adjusted with an addition of the material lost during the wet sieving method, the second part of the fine fraction.

**Sieve curve**

A sieve curve is a graph representing the passing percentages on the y-axis and the grain size on the x-axis. The x-axis has a logarithmic distribution. The points following from the sieve analysis are connected with straight lines in this semi logarithmic plot, see Figure B-2.

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**Figure B-2**: Sieve curve of sample C05-I. The blue circles are the measured passing percentages corresponding to the sieve sizes, the blue line is the approximated sieve curve.
The steepest part of the sieve curve contains the range of grain diameters that have the largest weight percentages of all the grain sizes. The steepness of the curve and the width of the largest part of the S-shape say something about the gradation of the sample. A very steep curve has little variation in grain sizes within the sample and is therefore called uniformly graded or poorly graded. A gentle wide curve has much variation in grain sizes and is therefore called well graded.

**Nominal diameters**

The nominal diameters of a sediment sample can be deducted from its sieve curve. The $D_x$ diameter, is the diameter for which $x\%$ of the sediment is smaller. Each $D_x$ diameter is thus found by reading the grain diameter from the sieve curve for the $x\%$ passing percentage, see Figure B-3. Some samples do not have a value (NaN) for the $D_{10}$ value. In these cases the $10\%$ passing percentage was not found, and thus the passing percentage of the smallest sieve ($63\,\mu m$) was larger than $10\%$. For the example sediment sample C05-I the following grain size diameters are obtained from the sieve curve:

<table>
<thead>
<tr>
<th>Sample: C05-I</th>
<th>$D_{10}$</th>
<th>$D_{30}$</th>
<th>$D_{50}$</th>
<th>$D_{60}$</th>
<th>$D_{90}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C05-I</td>
<td>163.51</td>
<td>233.53</td>
<td>294.5</td>
<td>332.31</td>
<td>514.74</td>
</tr>
</tbody>
</table>

Figure B-3: Sieve curve of sample C05-I. The red dashed line gives an example of the determination of the $D_{60}$. The red crosses are the approximated values of the nominal diameters.
B-2 Constructing a master sample

A ‘master sample’ is constructed by adding all the grain samples taken over the profile together (Medina et al., 1994). As the locations and the distribution of the sample locations differs over the profile, a weighing approach was used to construct the master samples. With weights based on the cross-shore length the measurement sample represents, using the nearest-neighbour approach based on cross-shore position to divide the profile to representative areas per measurement location (Figure B-4, shows an example). The weighing factor is equal to the representative area divided by the total area of the profile (Eq. B-1 and example Equations B-2). The grain size parameters can then be calculated by summing up all measurement values times their weighing factor (Eq. B-6).

Figure B-4: Example of construction of a master sample. Fictional transect Z with three measurement points is divided into three areas using the nearest-neighbour approach.

\[
\text{fac} = \frac{\text{point area}}{\text{transect area}} \quad (\text{B-1})
\]

\[
f_{acZ1} = \frac{2b}{(3a + 3b)} \quad (\text{B-2})
\]

\[
f_{acZ2} = \frac{(a + b)}{(3a + 3b)} \quad (\text{B-3})
\]

\[
f_{acZ3} = \frac{(2a)}{(3a + 3b)} \quad (\text{B-4})
\]

\[
D_{50} = \sum (D_{50,i} \times fac_i) \quad (\text{B-6})
\]
Differences within a measurement location

Grain size analysis is performed on at least 2 sediment samples per measurement location, using the sieving installation and the dry or the wet sieving method. In the analysis of the spatial distribution of the grain size parameters, the average grain size parameters per measurement location will be used. In this section the variation in grain size parameters at a measurement location is shown by use of the sample standard deviation.

A spatial plot of the sample standard deviation shows measurement locations with large variations in resulting grain sizes. Possible explanations of differences within a measurement location can be caused by lack of reproducibility of the sieving method, large variations in grain sizes in the area or the use of different sieving methods for samples of the same area. These theories are researched in this section.

C-1 Spatial variation of standard deviation per measurement location

The sample standard deviation (Eq. C-1) is used to express the variation of grain sizes within an area, based on a sample of the entire population. The number of analysed samples per measurement location is 2 for most locations, which will lead to a large error in the predicted standard deviation (60%).

\[ \sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n - 1}} \]  

(C-1)

The spatial distribution of the sample standard deviation of the different grain sizes does not show spatial trends, see Figures C-1. Though there is a clear difference in the magnitude of the standard deviation of the median grain size compared to the standard deviation of the D90 per measurement location. This is most likely caused by the sensitivity of the 90% passing percentage diameter to the consequences of the linear approximation of the sieve curve.

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Differences within a measurement location

Figure C-1: Spatial distribution of standard deviation of grain size diameters per measurement location

C-2 Standard deviation per measurement location related to depth

The standard deviations per measurement location are larger in the deeper part of the profile, though at a depth of -2m water depth there is a number of measurement locations with a larger standard deviation (Figures C-4 and ??). The larger variation around -2m water depth could be caused by the presence of a bar at that depth in these transects. The spatial variance in the position of a sample could then mean a difference between sampling at the bar or next to the bar and this would then lead to larger difference in the sediment composition of these samples.

The cause of the large standard deviation of point A09 (the blue circle with a standard deviation of more than 50 µm) can be explained by the use of 2 different sieving methods (dry and wet sieving technique). However there is no such logical explanation for the large standard deviation of point F10 (the yellow triangle with a standard deviation of more than 50 µm).

The average standard deviation of the median diameter within a measurement area is 17µm. Relative to the average median diameter (273 µm) this is a relative error of 6%. The standard deviation of the median diameter is larger than 25µm for 10 points, with a relative error of 9%. The differences between samples from the same measurement location can be caused by:

- Lack of reproducibility of the sieving method
- Variation of sediment characteristics within a sampling area
- Use of a different sieving method
C-3 Reproducibility of sieving method

The reproducibility of the used (dry) sieving method is tested by comparing the sieve results of two samples from the same oven dried sample.

A variation of grain size parameters within a sample could be caused by the way of transferring the sediment from the oven dried sample in the weighing scale or by irregularities in the sieving method. The assumption is made that the sampling of the sediment from the oven dried sample to the weighing scale does not introduce errors in the representation of the sediment characteristics of the sample. Thus this test set-up tests the reproducibility of the sieving method.

Table C-1: Grain size parameters of two samples of the same sample: E10-III

<table>
<thead>
<tr>
<th>Nominal diameter (µm)</th>
<th>D_{10}</th>
<th>D_{30}</th>
<th>D_{50}</th>
<th>D_{60}</th>
<th>D_{90}</th>
<th>c_u</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E10-III-I</td>
<td>217.7</td>
<td>284.2</td>
<td>347.0</td>
<td>377.9</td>
<td>573.6</td>
<td>1.74</td>
</tr>
<tr>
<td>E10-III-II</td>
<td>213.2</td>
<td>272.8</td>
<td>334.9</td>
<td>367.0</td>
<td>554.2</td>
<td>1.72</td>
</tr>
<tr>
<td>σ</td>
<td>3</td>
<td>8</td>
<td>9</td>
<td>8</td>
<td>14</td>
<td>0.01</td>
</tr>
</tbody>
</table>

The spread in median diameter of the two samples is 12 µm, the sample standard deviation is 9 µm. The largest difference between the two samples is in the D_{90} value. The uniformity coefficients of the two samples are very similar.

C-4 Variation within an area: same sieving method

Variation between the different sediment samples originating from the same measurement location can be caused by variation of sediment characteristics in this area.

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The measurements are taken with a maximum difference of 7 m from the measurement location, based on a maximum distance of 3 m from the measurement point, measured by GPS, and a distance of 4 m from the measurement location to the GPS receiver. The maximum distance between two sediment samples taken in the same measurement area can thus be 14 m.

A variation of grain size parameters within an area can be caused when sampling in an area with morphological features as bars and troughs with large differences in grain size parameters. In this case, some samples could be taken at a location with a different morphological signature (bar or trough).

Variations in grain size can also be caused by characteristics other than the grain size influencing the grain size analysis, like organic material or shell fragments. Organic matter can cause grains to stick together, resulting in larger grain sizes from the sediment analysis. The influence of organic matter on the grain size distribution is not looked into in this research. Shell fragments ending up in the larger sieves and weighed as sediment will also result in larger grain sizes from the sediment analysis. The effect of shell fragments on the grain size distribution is explained in Section 4-4-4.

**Measurement locations: D03 and D04** At the location of measurement point D03 and D04 a number of 6 samples were taken in total. The last 3 samples at each location were taken about 2 hours later than the first 3 samples. Though this is not apparent in the measurements, as the last 3 samples of D03 are within the range of the values of the first 3 samples. The last 3 samples of D04 cause a wider spread by 5 \( \mu m \).

**Figure C-5:** Sieve curves of the samples taken at locations D03 and D04. The roman numbers behind the sample location represent the sequence in which the samples were taken.

**Figure C-6:** Weight percentages of the different samples taken at location D04. The weight percentage in the fraction of 300-425 \( \mu m \) is fairly constant for all these samples.
Table C-2: Standard deviation of grain size parameters at locations D03 and D04

<table>
<thead>
<tr>
<th>Sample</th>
<th>$D_{10}$</th>
<th>$D_{30}$</th>
<th>$D_{50}$</th>
<th>$D_{60}$</th>
<th>$D_{90}$</th>
<th>$c_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D03</td>
<td>9</td>
<td>13</td>
<td>17</td>
<td>23</td>
<td>19</td>
<td>0.07</td>
</tr>
<tr>
<td>D04</td>
<td>8</td>
<td>12</td>
<td>16</td>
<td>21</td>
<td>18</td>
<td>0.06</td>
</tr>
</tbody>
</table>

The standard deviation within these measurement locations is larger than the standard deviation within a sample (9 $\mu m$ for the $D_{50}$), based on sample E10-III, see Section C-3. A large variation within a measurement area than within a sample means that variations within a measurement area can be measured.

The sieve curves from the different samples taken at D03 and D04 are not differing as much as appears on first glance from the sieve curves in Figure C-5. The weight percentages of some sieve fractions are very much alike, as can be seen from the parallel lines in the sieve curve, for example between 20 and 80% passing percentage. These percentages for location D04 correspond to the grain size between 300 to 425 $\mu m$. Parallel lines in a sieve curve point out that the weight percentage of sediment between these grain sizes is equal for the different samples. This is more easily visualised by using a histogram with weight percentages, see Figure C-6. From this figure it is clear that the weight percentage in the fraction between 300 and 425 $\mu m$ is fairly constant for all the samples taken at location D04.

Measurement locations: transect D To be able to place the variations within the area of D03 and D04 into perspective, the variations at the measurement locations D02 and D05 are discussed here, because these points surround the locations D03 and D04.

The values of the sample standard deviations of D03 and D04 are compared to the standard deviations of the other measurement locations of transect D in Table C-3. The variation of the grain size parameters within the area of D03 and D04 is comparable to the variation within the areas of most points in the D transect. Only the areas D08, D09, D10 stand out with a higher variation within the area, especially in the variation of the $D_{90}$ value.

Table C-3: Standard deviation of grain size parameters in transect D

<table>
<thead>
<tr>
<th>Sample</th>
<th>$D_{10}$</th>
<th>$D_{30}$</th>
<th>$D_{50}$</th>
<th>$D_{60}$</th>
<th>$D_{90}$</th>
<th>$c_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D02</td>
<td>6</td>
<td>4</td>
<td>6</td>
<td>5</td>
<td>8</td>
<td>0.06</td>
</tr>
<tr>
<td>D03</td>
<td>9</td>
<td>13</td>
<td>17</td>
<td>23</td>
<td>19</td>
<td>0.07</td>
</tr>
<tr>
<td>D04</td>
<td>8</td>
<td>12</td>
<td>16</td>
<td>21</td>
<td>18</td>
<td>0.06</td>
</tr>
<tr>
<td>D05</td>
<td>5</td>
<td>12</td>
<td>19</td>
<td>17</td>
<td>22</td>
<td>0.04</td>
</tr>
<tr>
<td>D06</td>
<td>3</td>
<td>6</td>
<td>9</td>
<td>13</td>
<td>8</td>
<td>0.05</td>
</tr>
<tr>
<td>D07</td>
<td>10</td>
<td>12</td>
<td>20</td>
<td>21</td>
<td>28</td>
<td>0.02</td>
</tr>
<tr>
<td>D08</td>
<td>8</td>
<td>18</td>
<td>29</td>
<td>28</td>
<td>54</td>
<td>0.07</td>
</tr>
<tr>
<td>D09</td>
<td>18</td>
<td>22</td>
<td>29</td>
<td>42</td>
<td>143</td>
<td>0.05</td>
</tr>
<tr>
<td>D10</td>
<td>16</td>
<td>20</td>
<td>19</td>
<td>18</td>
<td>106</td>
<td>0.03</td>
</tr>
<tr>
<td>D11</td>
<td>3</td>
<td>8</td>
<td>7</td>
<td>8</td>
<td>19</td>
<td>0.01</td>
</tr>
</tbody>
</table>

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C-5 Influence of different sieving method

Variation between the different sediment samples originating from the same measurement location can be caused by the use of a different sieving method.

The use of the wet or the dry sieving method on a sample influences the sieve curve. As an example measurement point A09 is presented here, as sample A09-I is sieved with the dry sieving method, while sample A09-II is sieved with the wet sieving method. The sieve curves of these samples are plotted in Figure C-7.

![Sieve Curves: A09](image)

**Figure C-7:** Sieve curves of samples at same location but with different sieving method - measurement location A09. Sample A09-I is sieved with the dry sieving method (red) and the wet sieving method is applied to sample A09-II (blue).

The standard deviation of the median diameters of the samples is 64 µm. The standard deviation within an area for sample points in a comparable area (F09 â– F10 and B09 â– B10) ranges from 7.5 to 71 µm, with an average of 23 µm and a standard deviation of 32 µm. The locations F09, F10, B09 and B10 are considered comparable to A09 because they are assumed not to be influenced directly by the Sand Motor and the water depth is in the same range.

The conclusion can be drawn that the large difference between the two sieve curves of the two different samples taken at A09 is caused by the difference in the sieving method. The standard deviation between the two samples of A09 sieved by different methods, is significantly larger than the standard deviation within comparable areas. A possible explanation of the large difference between the use of the wet and the dry sieving method is that fine particles stuck together when using the dry method. The fines in A09-I stuck together forming larger particles in the 425 µm sieve for example, causing a lower passing percentage at the 425
µm grain diameter for the A09-I sample and a lower passing percentage at 63 µm as well compared to the sediment analysis of the A09-II sample.

The high variation of the D$_{90}$ at some of the measurement locations (see Figure ??) can be explained by this theory: the dry sieving method was chosen, but apparently there was fine material present after all at these locations (D08, D09, D10, E09, C10, A09) and in retrospective it can be concluded that the wet sieving method should have been used on these samples.
Appendix D

Statistical tests to compare data sets

D-1 T-test

When the size of both data sets exceeds 30 number of elements, the normal t-test can be used. The calculated t-value (Eq. D-1) is compared with a tabulated t-value based on the degrees of freedom and whether the test is two-sided or one-sided. If the tabulated t-value is smaller than the calculated value the two data sets are significantly different.

\[
t_{cal} = \frac{|\bar{x}_1 - \bar{x}_2|}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \quad (D-1)
\]

\[
\bar{x}_i = \text{Mean value of data set } i \\
s_i = \text{Standard deviation of data set } i \\
n_i = \text{Number of elements in data set } i
\]

D-2 Cochran’s t-test

When the size of one or both of the data sets is smaller than 30 elements, the F-test (\(s_1^2 = s_2^2\)) is applied to see whether the standard deviations of the two data sets are similar. If this is the case the student’s t-test can be applied, and otherwise Cochran’s t-test. As the standard deviations of the data sets in this research are not similar only Cochran’s t-test is used and thus explained here. Cochran’s t-test uses the same equation to calculate the t-value as the normal t-test (Eq. D-1) but the tabulated value is calculated instead of looked up in a table, see Equation D-2. And the same test holds for Cochran’s t-test: if the (calculated) tabulated t-value is smaller than the calculated t-value the two data sets are significantly different.

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\[ t^*_\text{tab} = \frac{t_1 s_1^2/n_1 + t_2 s_2^2/n_2}{s_1^2/n_1 + s_2^2/n_2} \]  
\hspace{1cm} (D-2)

- \( t_i \) = \( t_{\text{tab}} \) at \( n_i - 1 \) degrees of freedom of data set \( i \)
- \( s_i \) = Standard deviation of data set \( i \)
- \( n_i \) = Number of elements in data set \( i \)
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