Seasonal changing sand waves and the effect of surface waves

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Abstract

Sand waves are wavelike subaqueous sediment structures that exist in large areas in shelf seas. Due to their characteristics sand waves can severely affect human offshore activities, such as navigation. This makes it important to understand the physical processes that shape and change sand waves. In field data, temporal variation in the migration and the shape of sand waves are found. Besides other factors, surface wave action might cause this variation.

In this study, a morphodynamic model and field data were used to investigate the importance of the surface waves on sand wave migration and shape. The field observations show that periods with surface waves can significantly affect the sand waves.

Model results indicate that the surface waves explain these changes partly. Possibly surface waves in combination with a variation in the tidal current will explain the effects in a larger extent.

Keywords: sand wave, surface wave, field data, numerical modelling

1 Introduction

The seabed of shallow shelf seas is rarely flat. When sediment is in good supply and tidal flows are sufficiently strong, wavelike subaqueous sediment structures, called sand waves, may occur. With a migration rate up to several tens of meters per year, a wave length of several hundreds of metres and a height up to 1/3 of the local water depth, sand waves can severely affect human offshore activities, such as navigation. This makes it important to understand the physical processes that shape and change sand waves, in order to improve management strategies of expensive operations such as e.g. the dredging of shipping lanes.

Empirical data showed that both temporal changes in currents and surface waves can affect the sand wave shape and migration. Van Dijk & Egberts (2008) describe a seasonal back and forth migration of sand waves that are located 50 km off the Dutch Coast. An example of asymmetry change due to current is given by Harris (1989), who found that Monsoon driven currents reversed the asymmetry and direction of migration of bed forms in the Adolphus Channel.

Van Dijk & Kleinhans (2005) find that the variability in dynamics between offshore and coastal sand wave sites may be explained by the relative contribution of current and wave action. Houthuys et al. (1994) find an average lowering of the sand wave height of 1.2 metres in a pre- and post storm study of the Middelkerke Bank in the southern North Sea near Belgium. The effect increased with decreasing water depth on the flank of the sand bank where the sand waves were superimposed upon.

Using an idealized sand wave model, Sterlini *et al.* (2009) showed that the relative rate of the M2 and the unidirectional tidal current has an influence on the bed form height and shape. Sterlini (2009) predicted lower bed forms for increasingly higher surface waves. Also, the surface waves were found to cause a higher migration rate for higher surface waves.

In the previous study by Sterlini (2009), surface waves were included, but their direction was always kept collinear with respect to the current. In reality, wave directions are variable. In this paper we present the model, including the free surface wave direction.

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The hypothesis is that variations in both currents as well as surface wave activity have a significant role in the sand wave shape and direction of migration. This research aims to quantify the role of surface waves, including both height and direction and which part must be attributed to other processes, such as variations in tidal currents. We use bathymetric and surface wave field data at two sites, the Varne (UK) and near Alkmaar (Netherlands Continental Shelf), together with an idealized model to investigate the effect of surface waves in more detail.

2 Methods

2.1 Bathymetry

The bathymetry data is interpolated from spatially distributed points to regular grids, using a kriging algorithm, using inhouse software that was especially designed to deal with large amounts of data (Van Dijk *et al.*, 2008). Resampled transects were used to determine shape characteristics by means of the Fast Fourier Transform (FFT). The FFT fits a discrete function through the points of the transect in order to separate the signal of sand waves, from large and small scale morphology (E.g. mega ripples and sand banks). For details on the separation method, see Van Dijk *et al.* (2008).

2.2 Sand Wave Model

The model used in this study is based on the model developed by Németh *et al.* (2006), further developed by Van den Berg & Van Damme (2006). Their work is based on analytical models such as made by Hulscher (1996) and Komarova & Hulscher (2000).

The model is a 2DV, non-linear, idealized, process-based model, named the Sand Wave Code (SWC).The latest refinement of this model was done by Sterlini (2009). In separate studies, she added surface waves and suspended sediment to the code.

This research focuses on the action of surface waves, using the version of the code that only described bed load transport with waves. A combination of waves and suspended sediment will be worked on later. This is justified to some extend, as bed load transport is considered the dominant mode of transport in offshore sandy tidal regimes where sand waves occur (Németh *et al.* 2002).

The initial model set up is as described in Sterlini *et al.* 2009. The flow of the model is calculated using the hydrostatic shallow water equation for 2DV flow. The domain setup is shown in Figure 1. The model uses periodic boundary conditions. Physically this represents the sand wave in between identical sand waves. The tidal flow is modelled as a sinusoidal current prescribed by means of a forcing. Boundary conditions at the bed disallow flow perpendicular to the bottom.

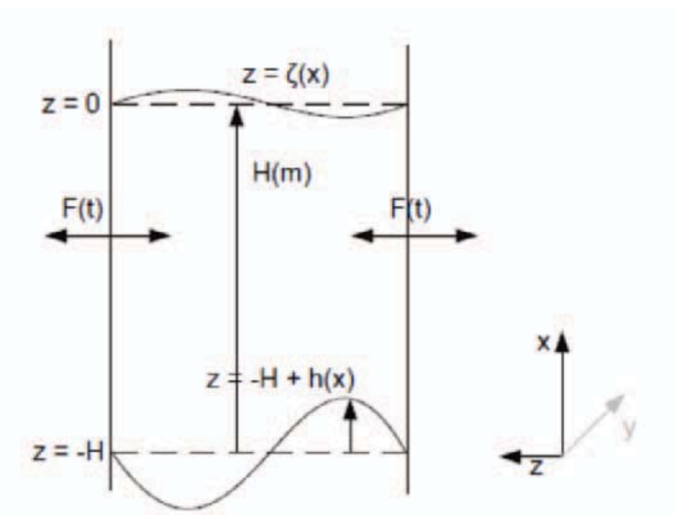

Figure 1: SWC domain set up

Further, a partial slip condition compensates for the constant eddy viscosity, which is known to overestimate the eddy viscosity near the bed. At the water surface there is no friction and no flow through the surface. Since the flow changes over a timescale of hours and the morphology over a timescale of years, the bathymetry is assumed to be invariant within a single tidal cycle. The flow and the sea bed are coupled through the continuity of sediment. Only bed load transport is taken into account, for equations we refer to Van den Berg and Van Damme (2006) and Sterlini *et al.* (2009).

As sand waves occur in relatively deep water with respect to wind waves, the wind waves are expected not to break. To implement the effect of surface waves we use the linear wave theory, i.e. monochromatic waves for which the linear approximation holds (ak<<1, a/h<<1 and a/k^2h^3<<1, where a is wind wave amplitude, k wavenumber and h local water depth). We assume that the currents will influence the wave characteristics, while the waves do not influence the currents (Mei 1999). With a given incoming wave period and direction, the wave number k and the wave energy per location over the sand wave are calculated by

$$\omega = Uk + \sqrt{gk \tanh(kh)}, \qquad \frac{d}{dx}\left(\left(U + C_g\right)\frac{E}{\sigma}\right) = 0$$
$$C_g = \frac{\omega}{2k}\left(1 + \frac{2kh}{\sinh(2kh)}\right), \qquad \omega = \frac{2\pi}{T} \tag{1}$$

Here U is the depth averaged current velocity, g the gravitational acceleration, E the wave energy, σ the intrinsic wave frequency, C_g and T represent the group velocity and the wave period of the surface waves respectively, and φ represents the angle between the waves and the tidal current. Via the surface wave height H_w and wave orbital velocity u_w, we finally determine the bed shear stress due to the wind waves, τ_w, by

$$E = \frac{1}{8}\rho g H_w^2, \qquad u_w = \frac{\omega H_w}{2\sinh(kh)}, \qquad \tau_w = \frac{1}{2} f_w u_w^2, \qquad f_w = 0.237\left(\frac{a}{2.5D}\right)^{-0.52} \tag{2}$$

Here f_w is the bed friction factor according to Soulsby (1997), and D is the grain size. Note that we use the volumetric bed shear stress. To combine both the current and the wave shear stress, we extend the sediment transport equation with an extra term, for the wind wave bed shear stress. This causes an extra transport by the tidal flow and affects the slope adjustment, both due to the stirring effect of the wind waves:

$$q_b = \alpha\left|\tau_{bf}\right|^{\frac{1}{2}}\left(\left|\tau_{bf}\right| + \gamma\left|\tau_{bw}\right|\right)\left(\frac{\tau_{bf}}{\left|\tau_{bf}\right|} - \lambda\frac{dh}{dx}\right) \tag{3}$$

In this we follow Roos *et al.* (2004) and Calvete *et al.* (2001), here rewritten for a z-coordinate dependent situation, i.e. for the bed shear stress τ instead of depth averaged velocity u. The bed load sediment transport and the bed shear stress due to the current are represented by q_b and τ_{bf} respectively and γ equals (½ + $\cos^2$(φ)) and represents the angle between the waves and the current.

3 Data from the Varne area

3.1 Bathymetry

The studied sand wave field in the Varne area is located in the Dover Strait, just north of a sand bank. The sand wave crests are perpendicular to the main direction of the asymmetric tidal flow. The sand waves have been recorded 3 times, and from the recordings two transects could be used for tracking changes in time, see Figure 2 (data supplied by the UK Hydrographic office).

The most northern transect has a length of 956m; the southern transect is 1091m long. The recording in October shows short and tall crested sand waves, the later recordings show broader and flatter crests (Figure 3). The time difference between the recordings of the northern transect was 66 days. The mean sand wave length in the area changed from 92 to 96m, the sand wave height was lowered with one metre from a mean value of 4.1m tot 3.1m. This is mainly due to a lowering of the sand wave crest, but also the troughs were lowered. Another interesting fact is that the horizontal asymmetry (L_{lee}/L_{stoss}) reversed, from 2.7 to 0.5.

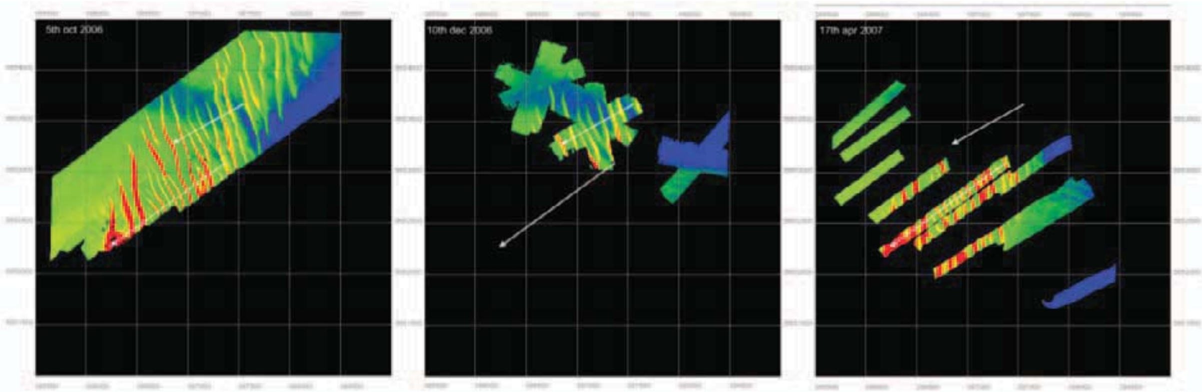

Figure 2: Bathymetry measurements in the Varne area. The white arrows indicate the used profiles.

Due to the shape change of the sand wave field, the migration of the troughs and crests is in different directions. The crests moved on average 25m to the North East (a speed of 139 m/y), while the troughs moved 12m to the South West (66 m/y). Note that the high migration rate values are mainly due to the shape change of the sand waves and not due to the migration of the total bed form.

For the southern transect, the average sand wave length remained 86m. The average sand wave height was also reduced by 1m, from 4.9m to 3.9m. The crest height was again reduced, while here the troughs were elevated suggesting a decay of the bedform. The sand waves show less horizontal asymmetry, which changed from 1.2 to 1.9. Both crests and troughs migrated to the North East with a rate of 22 and 32m/y respectively.

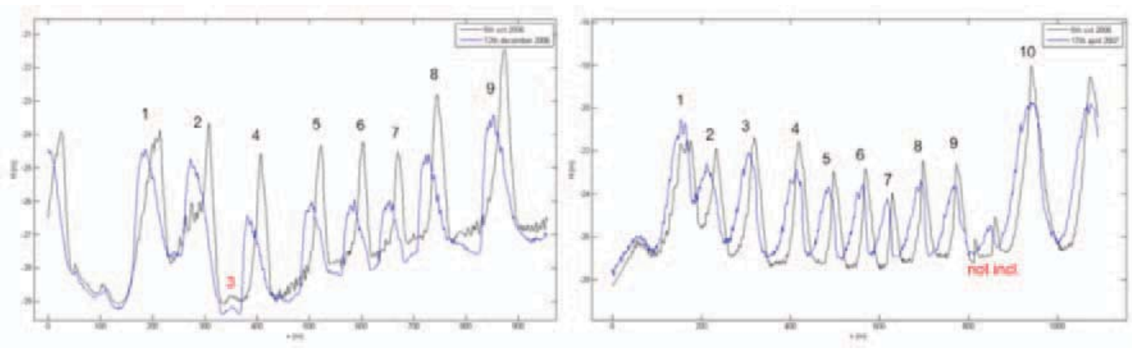

Figure 3: transects in the Varne area from the NE to the SW, corresponding to the white arrows in Figure 2.

3.2 Wave and weather data

We investigated the weather and wave climate before the three recordings. Periods of 66 days are used, equal to the shortest period between the different recordings. Wave characteristics were supplied by the UK Hydrographic office. Before the first recording (October 2006), the investigated 8 weeks before were weeks of calm weather, there was one short 2 day storm with waves higher than 2 meters. The wind direction was mainly from the south west. We assume this as a long period of calm weather. The recorded short crested and tall sand waves are therefore assumed to be fair weather sand waves.

In the period between the first and second recording, multiple storms with waves higher than 2m occurred. Most storm periods came from the south west (70% of the wind/waves), but approximately 20% of the wind/waves came from the north/north west. Mega ripples on the sand waves in the second recording (December 2006) suggest that the last migration direction of the sand waves was in the North Eastern direction.

Finally, the period before the recording in April 2007, contained of several stormy periods. In January-March waves came mainly from the South West, while just before the recording a North Eastern storm period took place. The migration of transect 2 over the period October 2006 to April 2007 was less then the migration of transect 1 over the shorter period (October – December), but significantly in the North Eastern direction.

3.3 Sand wave model results

Table 1 shows the parameter settings for the model runs. Values of the eddy viscosity A_v, the slip parameter S and the slope parameter λ are chosen according to Németh *et al.* (2002) as typical parameters for the Southern North Sea. It also summarizes the results of the model runs without surface waves.

Table 1: Parameter values and results for the model runs of the Varne area.

Parameter	Value	Unit	Results	no waves	with waves
Eddy viscosity	1.0e-2	m^2/s	FGM	210m	210m
Slip parameter	8.0e-3	m/s	Sand wave height	6m	6m
Slope parameter	1.7	-	migration	15m/y	22-45m/y
Tidal flow	1.0	m/s	L_{crest}/L_{trough}	0.78	0.94
Residual flow	0.05	m/s	L_{stoss}/L_{lee}	1.5	2.3
Water depth	30	m			

When waves are introduced in the model, waves of 1.4m/s have no significant effect on the sand wave shape. Waves of 2.8m/s have a significant effect. The sand wave crest reduces with approximately 0.5m in 40-50 weeks, while the trough depth is deepened by 0.4m in 30-40weeks. The result is a lower sand wave, but the total sand wave height remains more or less unchanged. The length of the crest increases due to the waves, from 92 to 102m. This results in a smaller horizontal asymmetry, the L_{crest}/L_{trough} goes from 0.78 to 0.94 when waves are included. When looking at the L_{stoss}/L_{lee} ratio, we see that the length of the stoss side of the sand wave is instantly affected by waves. The ratio goes from 1.5 to 2.3, and changes back when the wave height is reduced again.

Note that even without the waves, the sand wave crest and trough already vary in height in time.

When investigating the migration of the sand waves, smaller wind waves (1.4m/s) already affect the sand wave migration. Due to the asymmetric current there is already a background migration of 15m/y. When waves of 1.4m/s or 2.8m/s respectively are introduced, the migration increases to approximately 22m/y and 45m/y respectively. These values hold for waves that are collinear with the residual current. When waves were opposing the tidal migration direction, the migration was slowed down, but never reversed.

3.4 Discussion Varne area

When the results of the recordings and the model are compared we see that the wave length predicted by the model is a factor 2 to 2.5 larger than the observed length (210m vs. 86-96m), the sand wave height is overestimated by 1-3m (6m vs. 3.0-4.9m), and although the crest lowered in the model, this was counteracted by the lowering of the trough. The total sand wave height was therefore not affected in the model, while the recordings show a lowering of 1m. Finally the migration was estimated by the model between 20 and 45m/y, while the recordings showed migration rates of 66-139m/y and 22-32m/y depending on the transects. Note however, that the high values of Transect 1 (66-139m/y) were mainly caused by the change in shape and not by the migration of the bedforms.

4 Data from the Alkmaar area

4.1 Bathymetry

The Alkmaar area is located about 50km out of the Dutch coast near Alkmaar. The sea floor ranges between 25 and 30m below mean sea level. The recorded area is 2x2.5km and was recorded 5 times between March 2001 and September 2002 (Figure 4). There was no systematic change of the sand wave shape in the area over the whole period, but sand waves migrated back and forth in time. The average values of the area are a sand wave length of 222m, a height of 1.79m and a L_{stoss}/L_{lee} of 3.6. The average migration rate over the whole period was 1.6m/y, but varies over the year with maxima migration of the pattern of 4.5m/y and of 12.2m/y for individual sand waves. In general the crest and trough of sand waves show the same migration rate and direction.

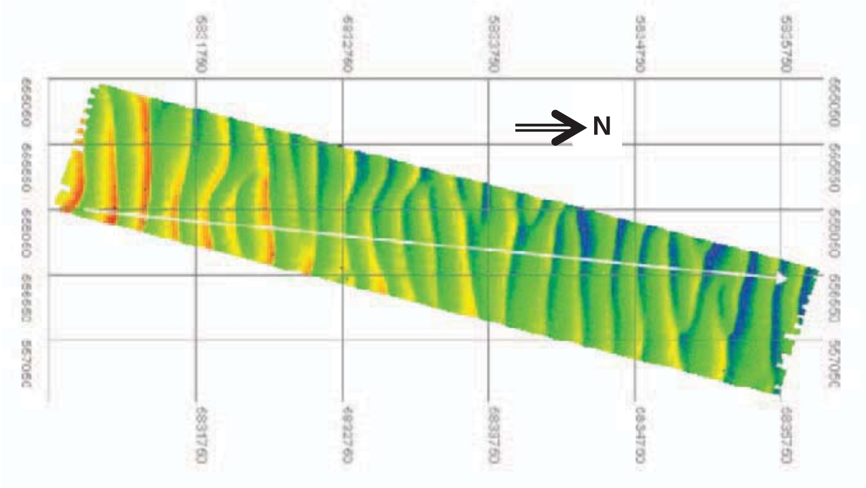

Figure 4: Area overview of the Alkmaar area

4.2 Wave and weather data

Wave data from www.waterbase.nl show that waves in general are directed towards the north east and the south east. In the four periods between the recordings the wave energy was primarily towards the south east between July 2001 and April 2002. From March 2001 to July 2001 and from April to September 2002 the wave energy was more equally distributed between the north east and the south east.

Investigating the conditions in this area showed a strong correlation between the wave energy and the residual current in the flow. The asymmetric tide has a symmetric part of 0.5m/s and a residual current of 0.05m/s. Investigating the flow data however showed that in case of high wave energy, the residual current could be up to 4 times larger. Most likely this combination of wave energy and higher flow conditions cause the migration of the sand waves in various directions.

4.3 Sand wave model results

Unfortunately we are currently unable to include this correlation between the waves and the current in the SWC. Runs have therefore been carried out with a constant residual current on top of the symmetric tidal current and waves. Waves were used comparable to measured waves near IJmuiden (De Leeuw, 2005). Different wave heights and periods were used, corresponding to different chances of occurrence. Table 2 shows the parameter settings and the results.

Although the preferred wave length that was found was 280m, simulations were carried out with a wave length of 220m to represent the data better. This, because the length also influences the sand wave height due to a maximum possible angle. Still the sand wave height is largely overpredicted both with and without waves and residual currents. When a symmetric tide is simulated (residual current of 0m/s) the sand waves grow to 12 m high and waves reduce the height to 10 and 9m for small and large waves respectively. When the residual current is included, leading to an asymmetric tide, we see that wave inclusion leads to higher sand waves (8.5 and 9.5m, respectively without and with waves).

Table 2: Parameter values and results for the model runs of the Alkmaar area.

Parameter	Value	Unit	Results	no waves	with waves
Tidal flow	0.5	m/s	FGM	280m (used 220m)	280m (used 220m)
Residual flow	0.00 / 0.05	m/s	Sand wave height	12-8.5m	9,10 – 9.5m
Water depth	28	m	migration	0-2m/y	4-11m/y

Migration under low waves is 0-2m/y under a symmetric tide. The direction depends on the wave direction and can be in both directions. Under an asymmetric tide, waves cause a migration of 4-11m/y when in the same direction of the residual current. Opposing waves will slow down the migration but no longer cause migration in the opposite direction. Migration under high waves is larger, but due to their low frequency of occurrence, they are not incorporated here.

With an asymmetric tide and waves, the sand wave crests become wider and lower. With a symmetric tide the effect of waves was not significantly changing the shape. The L_{lee}/L_{stoss} value was 1.0 under an symmetric tide and could be changed to slightly smaller then 1.0 when opposing waves were introduced. With the residual current and low waves the L_{lee}/L_{stoss} value was 3.5.

4.4 Discussion Ecomorf 3 area

Although the sand wave height is nearly overpredicted by a factor 6, other characteristics are well described by the model. The predicted sand wave length (280m) is relatively close to the observed (214m) and the same holds for the migration rate (4-11m/y and 4.5-12.2m/y) and horizontal asymmetry (3.5 and 3.6).

5 Discussion

In the Varne area, the SWC shows a lowering of the sand wave crests due to surface waves. However, this lowering needs about 30weeks of storm conditions, while in the data the lowering of the crests resulted from a much shorter periods with storm conditions in the order of days. One possible explanation might be that the combination with suspended sediment load is not included in the model. For example Tonnon *et al.* (2007) suggest that this is a key process that causes flattening (and lowering) of the sand wave.

The two areas studied in this paper differ mainly in the tidal strength. Still the sand waves show very different characteristics (wave length and height) and also show a different reaction to storm conditions. The Varne area mainly reacts by a change in the sand wave profile, while the Alkmaar area only shows a back and forth migration. The reasons for this are not yet clear, one option might be the saturation of the sand waves. As Van Dijk & Kleinhans (2005) noted the Ecomorph3 sand waves are fairly saturated, their shape is not affected as much as the possible less saturated sand waves in the Varne area. Another option might still be the flow velocity, due to which changes are induced on the sand wave shape quicker and stronger. Neither theories are confirmed by the model results. Predictions suggested much higher sand waves in the Alkmaar area and a change in the sand wave height up to 3m, while the lowering in the Varne area was less than 1m, and the predicted sand wave height was much closer to the observed value.

As shown by e.g. Bowden (1956) surface waves can also cause and extra current to flow. In the used SWC it is not possible to include a fluctuating residual current coupled to the surface waves. However as shown by Sterlini et al. (2009) this might have a large effect on the sand wave characteristics. Further research to this effect will be carried out.

6 Conclusion

In this study, a morphodynamic model and field data were used to investigate the importance of surface waves for sand wave migration and shape. The field observations show that periods with surface waves can significantly affect the sand waves. In the case of the Varne area the effect was both a change in the sand wave shape and (local) migration. In the case of the Alkmaar area the effect was only found in a seasonal variation in migration.
Model results indicate that the surface waves explain these changes partly. Waves in the direction of the residual tidal current add to migration. Waves opposing the residual current reduce the migration. Sand waves can be lowered up to half a metre. Possibly surface waves in combination with a variation in the tidal current will explain the effects in a larger extent.

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8 References

Bowden, K.F., “The Flow of Water through the Straits of Dover, Related to Wind and Differences in Sea Level”, Royal Society Publishing, 1956

Calvete, D., Falqués, A., de Swart, H.E., Walgreen, M., 2001. Modelling the formation of shoreface-connected ridges on storm-dominated inner shelves. Journal of Fluid Mechanics 441, 169–193.

De Leeuw, C.J., 2005. Model predictions of wave-induced sediment transport on the shoreface. Msc thesis, University of Twente.

Harris, P.T., 1989. Sand wave movement under tidal and wind-driven currents in a shallow marine environment: Adolphus Channel, northeastern Australia. Continental Shelf Research 9 (11), 981–1002.

Houthuys, R, Trentesaux, A. and De Wolf, P., 1994. Storm influence on a tidal sandbank's surface (Middelkerke Bank, southern North Sea), Marine Geology, p. 23-41, 1994

Hulscher, S.J.M.H., 1996. Tidal-induced large-scale regular bed form patterns in a three-dimensional shallow water model. Journal of Geophysical Research 101, 727–744.

Komarova, N.L., and S.J.M.H. Hulscher, 2000. Linear instability mechanisms for sand wave formation, Journal of Fluid Mechanics, 413, 219–246.

Mei, C.C., 1999. The applied dynamics of ocean surface waves. Vol. 1 of Advanced Series on Ocean Engineering. World Scientific Publishing Co Pte Ltd.

Németh, A.A., Hulscher, S.J.M.H. and De Vriend, H.J., 2002. Modelling sand wave migration in shallow shelf seas, Continental Shelf Research, 22 (18), 2795–2806.

Németh, A.A., Hulscher, S.J.M.H. and Van Damme, R.M.J., 2006. Simulating offshore sand waves. Coastal Engineering 53, 265–275.

Roos, P.C., Hulscher, S.J.M.H., Knaapen, M.A.F., 2004. The cross-sectional shape of tidal sandbanks: Modeling and observations. Journal of Geophysical Research 109 (F02003, doi:10.1029/2003JF000070).

Soulsby, R., 1997. Dynamics of marine sands, a manual for practical application, Thomas Telford.

Sterlini, F., 2009. Modelling sand waves variation, Ph.D.thesis, University of Twente, The Netherlands.

Sterlini, F., Hulscher, S.J.H.M., and Hanes, D.M. (2009). Simulating and understanding sand wave variation: A case study of the Golden Gate sand waves. Journal of Geophysical Research, 114 (F02007,doi:10.1029/2008JF000999).

Tonnon, P.K.,L.C. Van Rijn, and D.J.R. Walstra, 2007. The morphodynamic modelling of tidal sand waves on the shoreface, Coastal Engineering, 54,279–296.

Van den Berg, J., Van Damme, D., 2006. Sand wave simulations on large domains. In: Parker, Garcia (Eds.), River, Coastal and Estuarine Morphodynamics: RCEM2005.

Van Dijk, T.A.G.P. and Kleinhans, M.G. (2005). Processes controlling the dynamics of compound sand waves in the North Sea, Netherlands. Journal of Geophysical Research - Earth Surface, 110 (F04S10,doi:10.1029/2004JF000173).

Van Dijk, T.A.G.P. and P.J.P. Egberts, 2008. The variability of sand wave migration in the North Sea, in Marine Sandwave and River Dune Dynamics III: MARID2008, edited by D. R. Parsons, T. Garlan, and J. L. Best, pp. 63-67, 2008.

Van Dijk, T.A.G.P., Lindenbergh, R.C. and Egberts, P.J.P., 2008. Separating bathymetric data representing multiscale rhythmic bed forms: A geostatical and spectral method compared. Journal of Geophysical Research, 113 (F04017,doi:10.1029/2007JF000950).