On the effect of wind waves on offshore sand wave characteristics

F. Van der Meer & S.M.J.H. Hulscher
Water Engineering and Management, University of Twente, the Netherlands

N. Dodd
University of Nottingham, UK

ABSTRACT: Offshore sand waves are bed patterns that occur in shallow seas. They show both spatial and temporal variation in their characteristics such as their height (1-10m), length (100-800m), asymmetry and migration rate (1-10m/y). The reason for this variation is still not fully understood. Due to the different environmental processes that are incorporated in our present sand wave model, parts of this variation can be modelled and understood in more detail (Németh et al. 2007, Van der Meer et al. 2007). At present, one of the largest drawbacks of our model is the overprediction of the sand wave heights, especially in shallow water (around 15 meter water depth). A possible explanation for this overprediction is the absence of wind and weather influences. Though up till now wind waves are mostly assumed to be negligible, no studies are available investigating their effect on the evolution of sand waves in detail. Especially under storm conditions and in relatively shallow water wind waves could influence the sand waves. Therefore we implemented wind waves in our non linear sand wave model to investigate the influence of wind waves on the various phases of sand wave evolution. Results show that though wind wave energy increases over the sand wave crests, the effect of wind waves on the sand wave shape and evolution is negligible.

1 INTRODUCTION

1.1 *Sand waves*

Offshore sand waves are bed patterns that occur in shallow seas. The wavelengths of these bed forms vary between 100 and 800 metres, and heights can reach up to one third of the water depth (i.e. a maximum of around 10 metres in 30 metres of water). These characteristics, together with the fact that sand waves can migrate several metres per year and that they cover the majority of e.g. the Southern North Sea (Van der Veen et al. 2005), mean that they affect human activities in shallow seas. Therefore, we aim to model and so better understand the dynamics of these sand waves.

1.2 *Wind waves*

Offshore in shallow seas, under normal conditions short surface waves rarely interact with the sea bed. As the water depth is in the order of tens of metres, sediment is mainly transported as bed load with the current. However, during storms, wind waves are considered to act as a stirring mechanism for sediment, such that the sediment transported by the currents increase if wave energy increases. In this case sand waves might be affected by the wind waves and, in return, wind waves might be affected by the sand waves. This can happen due to a changing water depth, but also due to a changing current. If we take into account that sand waves can significantly change both the local water depth and with that the current velocity (Hennings et al. 2000), wind wave characteristics are expected to change over sand waves and possibly influence the sand wave shape. Field observations confirm this idea. For example Passchier & Kleinhans (2005) concluded that the sand wave morphology close to the coast of the Netherlands is a function of the general wind wave climate and measurement of Harris (1989) already show that sand waves close to Australia change their asymmetry, most likely as a response to the wind driven currents during the trade and monsoon season.

1.3 *Goal*

In this paper we are interested in the possible influence of wind waves on sand wave evolution. Therefore, we model wind wave effects in a non linear sand wave model, to investigate the influence of wind waves on the various phases of sand wave evolution. We will start by describing the general model and the extensions made to include the wind waves in Section 2. In Section 3 the results will be presented, followed by discussion of the results and conclusions in Section 4 and 5 respectively.

2 METHOD

In this section we will briefly describe the background of the model (section 2.1), for further details we refer to Van den Berg & Van Damme (2006) and Van der Meer et al. (2007). In section 2.2 the inclusion of wind wave effects will be described.

2.1 *Sand wave model*

The Sand Wave Code (SWC) used in this project is based on an idealized model by Németh et al. (2006) and further developed by Van den Berg (2006). It is a two dimensional vertical model, which is developed specifically to describe sand wave evolution from its generation, to its fully grown state.

For sand wave fields in the Southern part of the North Sea the SWC has shown good results in describing the wavelength, height, shape characteristics and migration (Van den Berg 2006, Németh et al. 2007, and Németh et al. 2006).

Sand wave formation is explained as self organisation due to interaction between a sandy seabed and a tidal flow. Sand waves occur as free instabilities in this system, i.e. there is no direct relation between the scales related to the forcing (tide) and those related to the morphological feature (sand wave) (Dodd et al. 2003). Sand wave occurrence can be understood only if the feedback mechanism between the forcing and the seabed is taken into account. Hulscher (1996) described this mechanism of self organization for sand waves, where residual vertical vortices play a crucial role.

In short the process is as follows. Starting from a flat bed with an oscillating current, small perturbations of the sea floor cause small perturbations in the flow field and vice versa. The bed can be either stable, which means that all bed perturbations will be damped or unstable, which means that certain bed perturbations will grow and the sea bed is changed.

If perturbations are unstable the flow field is changed such that, averaged over the tidal cycle, small vertical residual circulation cells occur (Fig. 1). These cells cause small net transport to the crests of the perturbation, thereby causing growth. Depending on the circumstances such as flow velocity and water depth, perturbations with different lengths will show different growth/decay rates. The fastest growing mode is the perturbation which triggers the fastest initial growth. For small amplitude perturbations, growth can be described as linear, though as sand waves grow larger, non-linear effects become important. However, there are several indicators that seem to imply that sand waves are only weakly non-linear: their amplitude is generally smaller than 20% of the water depth and the predicted fastest growing wave length (growth in height) is close to the observed wave length. As their slopes are gentle there is no flow separation. Assuming weak non-linearity, the initially dominating wavelength will be close to the one dominating in the non-linear regime. Subsequently, the fastest growing mode provides the dominant sand wavelength, which is found to be close to the dominating one in reality for weakly non linear systems (Dodd et al. 2003).

The SWC simulates this process from the initial disturbance to the final sand wave shape that is in equilibrium with the flow. The SWC consists of the hydrostatic flow equations for 2DV flow. 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. Further, a partial slip condition compensates for the constant eddy viscosity, which is known to overestimates 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. Note that here the bathymetry depends on time, in contrast with the calculations for the flow. Only bed load transport is taken into account, following Komarova & Hulscher (2000). For equations we refer to Van den Berg & Van Damme (2006) and Van der Meer et al. (2007).

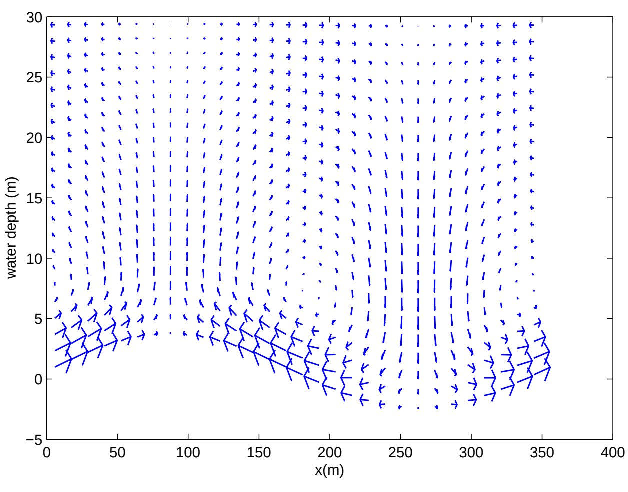

Figure 1. Residual circulation averages over one tidal cycle. In this unstable case the cells, formed due to the interaction between the flow and the bed perturbation, will lead to growth of the bed perturbation

2.2 *Wind waves*

As sand waves occur in relatively deep water with respect to wind waves, the wind waves are expected not to break. For the cases shown in Section 3 this holds though in some other cases this was not valid. Waves can break and even be blocked and swept back in the relatively deep water over the sand wave due to the current that is in the opposite direction for half of the tidal cycle (see Section 4).

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 amplitude, k wavenumber and h local depth). We assume that the waves and 2DV current are collinear. The absolute frequency of the waves, ω, is assumed to be constant and the wave action, E/σ, is a conserved quantity (because there is no wave breaking considered in the model). Furthermore we assume that the currents will influence the wave characteristics, while the waves don't influence the currents (Mei 1999). With a given incoming wave period the wave number is calculated using Equation 1. Knowing k, we can find the wave energy per location over the sand wave with Equation 2. Uk represents the Doppler effect. This holds especially for small wave periods and high current velocities.

$$\omega = Uk + \sqrt{gk\tanh(kh)} \tag{1}$$

$$\frac{d}{dx}\left(\left(U + C_g\right)\frac{E}{\sigma}\right) = 0 \tag{2}$$

$$C_g = \frac{\omega}{2k}\left(1 + \frac{2kh}{\sinh(2kh)}\right) \tag{3}$$

$$\omega = \frac{2\pi}{T} \tag{4}$$

Here ω is the absolute wave frequency, U is the depth averaged current velocity, k the wave number of the surface waves, g the gravitational force, and h the water depth. The wave energy is denoted by E, σ is the intrinsic wave frequency and C_g and T the group velocity and the wave period of the surface waves respectively. With equation 5 we can find the surface wave height H_w at different locations in time. With this wave height the shear stress at the bed due to the wind waves is defined using the wave orbital velocity (Equations 6 and 7).

$$E = \frac{1}{8}\rho g H_w^2 \tag{5}$$

$$u_w = \frac{\omega H_w}{2\sinh(kh)} \tag{6}$$

$$\tau_w = \frac{1}{2} f_w u_w^2 \tag{7}$$

$$f_w = 0.237\left(\frac{a}{2.5D_{50}}\right)^{-0.52} \tag{8}$$

Here u_w is the flow velocity due to the surface waves just above the bed, τ_w *is* the bed shear stress due to u_w, f_w is the bed friction factor according to Soulsby (1997), a is the surface wave amplitude (equal to half of H_w) and D_{50} is the medium grain size. Note that we use the volumetric bed shear stress.

To combine both the current and the wave shear stress , we follow Soulsby (1997):

$$\tau_t = \tau_c\left(1 + \left[1.2\left(\frac{\tau_w}{\tau_w + \tau_c}\right)^{3.2}\right]\right) \tag{9}$$

Where τ_t and τ_c represent the total bed shear stress and the bed shear stress due to the current respectively.

As can be seen in the equations, the linear approximations don't hold for waves that are blocked or swept back by the current, leading to wave breaking and other non-linear effects. This occurs especially for higher opposing currents and small wave periods (Peregrine 1976, Chawla & Kirby 2002). Cases in which this happens are excluded from the results in Section 3 as they can not be described with the used wind wave model.

3 RESULTS

The effect of wind waves is investigated and a sensitivity analysis is carried out for the influence of the current speed, the water depth, the wind wave period and initial height, and storm periods. Table 1 shows the initial parameter settings for the simulations.

Table 1. Parameter settings for the model runs unless stated different in the text.

Parameter	value	dimension
U	1.0	m/s
A_v	0.03	m^2/s
S	0.01	m/s
λ	1.7	-
h	15	m
H_{wind}	1.0	m
T	7.0	s

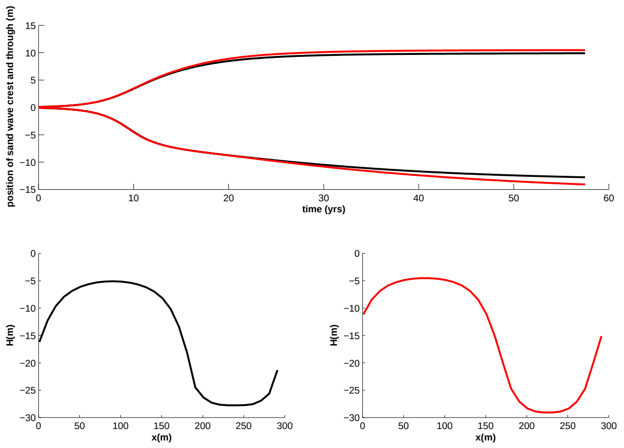

Figure 2. Sand wave growth (top) and shape (bottom) with (left) and without (right) waves. Water depth is 15 m, averaged tidal current 1.0 m/s

3.1 *Including wind waves*

Figure 2 shows the effect of wind waves on a sand wave in 15 m water depth. When wind waves are included the wave length stays the same and also the shape is mostly identical between the case with and without wind waves. However, the sand wave height is lower if wind waves are included (22 m instead of 24 m). Note that this height is still far from realistic values for 15 m water depth (in the order of 5 m, Wilkens 1997).

Figure 3 shows the wave energy over the sand wave during one tidal wave. The thick line indicates the average magnitude. The figure clearly shows the increase of wave energy over the top of the sand wave. Because of that the wind wave height increases with 0.3 m at maximum tide, leading to an increase of the bed shear stress. For the maximum current in the direction of the waves, the wave height decreases by 0.1 m. This increase/decrease is due to the shallower water and the increasing opposite current.

Figure 4 shows the individual effect of these two factors. Taking C_g as a constant (second box) shows that the variation during the tide is smaller. The migration increases leading to a more asymmetrical shape of both the sand wave shape (not shown) and wave energy distribution. The maximum wave energy is still at the sand wave crest. Taking U as zero in Equation 2 results in a constant value over the tide, but different depending on the location (third box). No migration occurs in this situation.

Though there is a clear increase in wave energy the effect on the sand wave form and evolution is small. Wave length and shape are unaffected and the wave height decreases with approximately 10%.

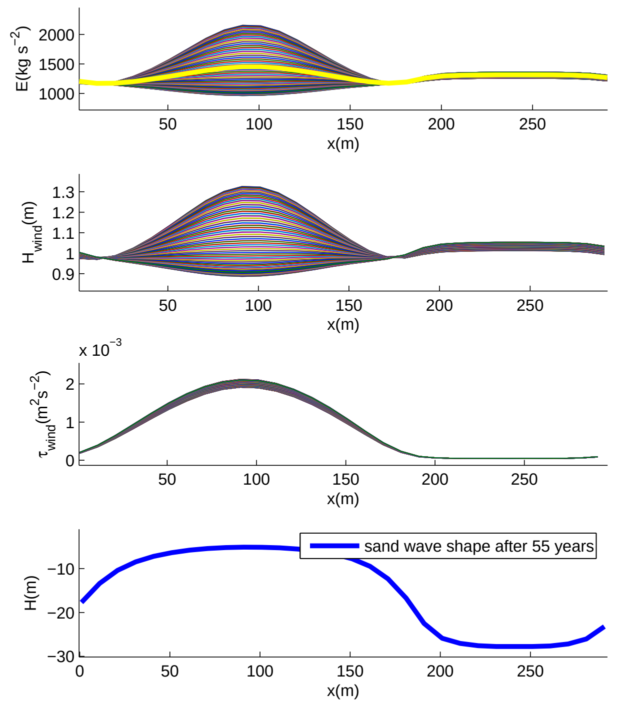

Figure 3. Wave energy, height and bed shear stress over a sand wave. The envelope in values indicates the different values over one tidal cycle.

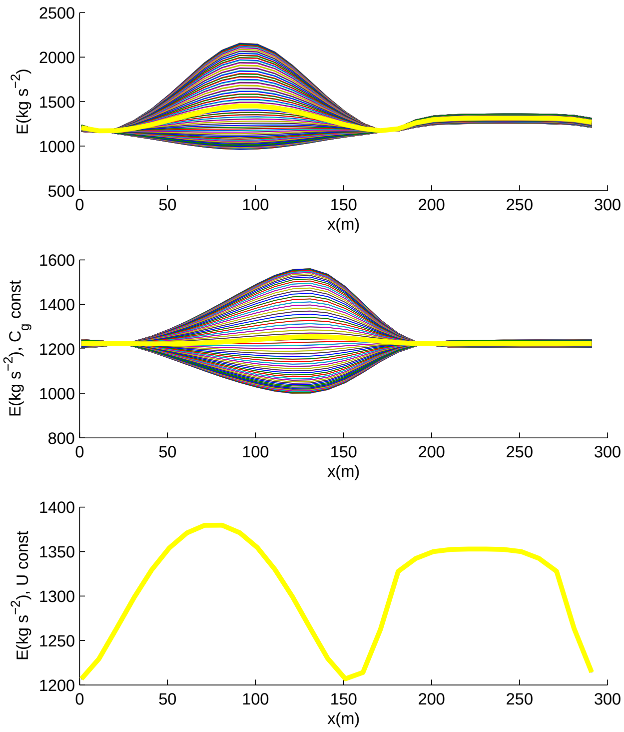

Figure 4. Wave energy over a sand wave, including both the influence of water depth and current (top), and excluding water depth (second) or current (third) effects. The envelope in values indicates the different values over one tidal cycle. Note that the sand wave shapes for the three situations are different, leading to a different location for the maximum wave energy (see text for more explanation).

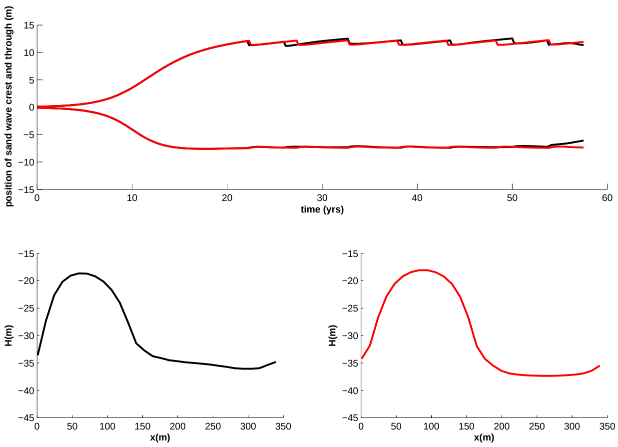

Figure 5. Sand wave growth (top) and shape (bottom) with (left) and without (right) waves. Water depth is 30 m, averaged tidal current 1.0 m/s.

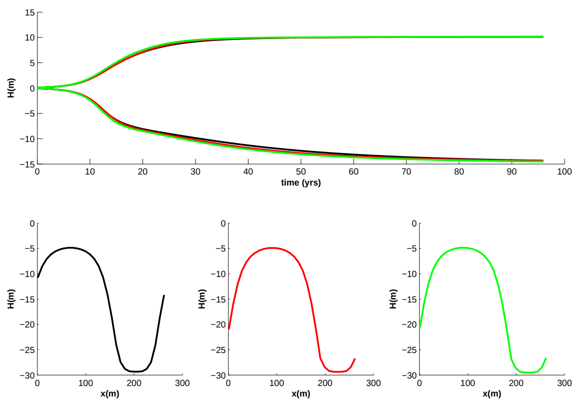

Figure 7. Sand wave growth (top) and shape (bottom) with a wave height of 0 m (left), 5.0m (middle) and 7.0 m (right), all for a water depth of 15 m and a depth averaged current of 0.5 m/s at maximal tide.

3.2 *Sensitivity*

Figure 5 shows the sand wave growth for a water depth of 30 m, with and without waves. Though different from the 15 m water depth case, the wind waves don't play an important role in this difference. Again sand wave length stays the same when wind waves are included, and the sand wave height is identical. The shape is slightly smoother without the wind waves, but not significantly different.

When the tidal current speed is changed from 1.0 to 0.5 m/s (maximal current, depth averaged), we see an initial slower growth of the sand wave, but the same final shape is reached after about 30 years (results are not shown). The influence of the wind waves is not increasing for a decreasing current.

Figure 6 shows the effect of different wind wave conditions, ranging from very mild weather (wind wave period of 4 seconds and wave height of 0.5 m) to extreme wind waves (period 12 s and height 2 m). Figure 6 shows that the influence on sand waves

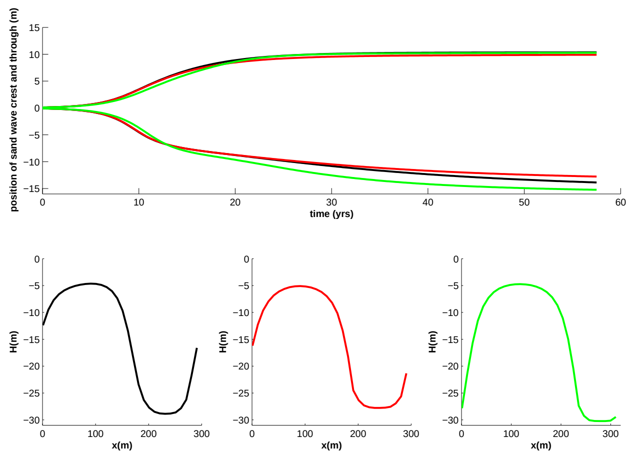

Figure 6. Sand wave growth (top) and shape (bottom) with a wave height and period of 0.5m and 4 s (left) , 1.0m and 7 s (middle) and 2 m and 12 s (right).

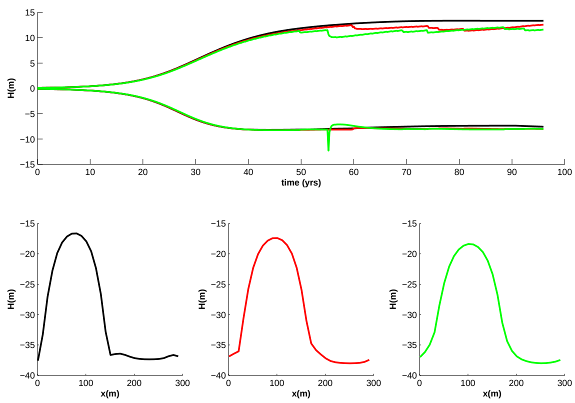

Figure 8. Sand wave growth (top) and shape (bottom) with a wave height of 0 m (left), 5.0m (middle) and 7.0 m (right), all for a water depth of 30 m and a depth averaged current of 0.5 m/s at maximal tide.

stays negligible even for the largest wind waves. No constant lowering of the sand wave is observed, and only the shape seems to be changed and slowly deforms to a flatter and longer crest. However, the final sand wave forms show a clear migration in the direction of the wind waves, which increases for increasing wind wave energy.

3.3 *Storm periods*

In reality wind waves of long period and large height only occur in short periods during the year. Therefore simulations were done, in which the waves were only included 10 weeks per year. This is still an overestimation of the storm season, but gives a good indication of the effect and also keeps the fast computation time. The results are shown in Figures 7 and 8, for 15 and 30 m water depth respectively, both with a current of 0.5 m/s. The Figures show different effects. First, for a water depth of 15 m, the wind waves slightly increase the growth rate but don't change the final sand wave height. Second, in the 30 m water depth case, the main difference is the difference in sand wave height, were the cases with wind waves show lower sand waves and more instabilities. It seems that the periods with wind waves destabilise the sand waves and lower the crest with approximately 5%. Though difficult to see in the Figures 7 and 8, the wind waves cause migration of the sand waves in the direction of the wind waves. On average the migration is 0.2 and 0.3 m/y for the 30 m water depth case, respectively for a wind wave height of 5 and 7 m, and 0.2 m/y for both wind wave cases in 15 m water depth. Note that both a wave height of 5 and 7 m is unrealistic for a time period of 10 weeks, but are used here as an extreme research case.

4 DISCUSSION

To test the influence of wave breaking Equation 2 was extended to Equation 10 with D as defined in Equation 11, following Chawla (2002) as the wave breaking will occur due to the opposing current instead of due to the water depth.

$$\frac{\partial E}{\partial t}+\frac{d}{dx}\left(\left(U+C_g\right)\frac{E}{\sigma}\right)=-\frac{D}{\sigma} \tag{10}$$

$$D=\frac{\beta}{8\pi}\rho g H^3\sqrt{\frac{gk}{\tanh kh}} \tag{11}$$

In this, D is the energy dissipation rate per unit area, and β is a non dimensional parameter (0.1).

No changes were observed in the simulations, larger than 1-2%. Still in some cases the included wind wave model was insufficient. This occurred when wind waves were blocked or even swept back by an opposing current. This was for example the case for a 30 m water depth and a wave height and period of 0.5 m and 4 s (results not shown) and for the inclusion of a residual current (not shown). In both cases the currents were strong enough to block the wind waves. In this cases the strong current is most likely overruling the effect of the relatively small wind waves on the sand waves. However the used wind wave model is unable to simulate this non linear wind wave behaviour.

Even for the largest wind waves tested, the effect on the sand wave evolution is small. The total bed shear stress is determined by the bed shear stress due to the current and the bed shear stress due to the wind waves (Eq. 9). Even for severe wind waves the wind wave influence is smaller than the current influence. When the wind wave bed shear stress was artificially increased by a factor 100, the result show a tendency to decrease the sand wave height with approximately 20% compared with a case without wind waves. Here again the model was unable to find a final state.

Though the effect on the sand wave shape is small, the wind waves are able to cause migration of the sand waves with several decimetres per year in the case of storm and calm weather periods. This coincides with observed sand wave migration during storms, though horizontal precision of the measurements is often less accurate than this (Németh 2002, Dorst et al. 2006 and references herein).

The overestimation of the sand wave height seems not to be caused by the exclusion of wind waves. Another option is the effect of suspended load that is currently not taking into account. Including suspended sediment might also increase the effect of wind waves as sediment is transported over larger distances higher in the water column, which may add to the diffusive effects.

5 CONCLUSIONS

Modelling sand waves in shallow water shows an overestimation of the sand wave height. In this study the possible influence of wind waves on the sand wave characteristics is investigated. Though the wind wave energy clearly increases over the sand wave crest, the sand wave height, length and shape is hardly affected by this increase in wave energy. The overestimation of the sand waves therefore must be caused by another factor, e.g. a combination of wind waves and suspended sediment transport.

6 ACKNOWLEDGEMENTS

This research is supported by EncoraNL and the Technology Foundation STW, applied science division of NWO and the technology programme of the Ministry of Economic Affairs. Their support is gratefully acknowledged.

7 REFERENCES

Chawla, A. and Kirby, J. T. (2002). Monochromatic and random wave breaking at blocking points. *Journal of Geophysical Research*, 107(C7, doi:10.1029/2001JC001042).

Dodd, N., Blondeaux, P., Calvete, D., de Swart, H., Falques, A., Hulscher, S. J. M. H., Rozynski, G., and Vittori, G.

(2003). Understanding coastal morphodynamics using stability methods. *Journal of Coastal Research*, 19(4):849-866.

Dorst, L. L., Roos, P. C., and Hulscher, S. J. M. H. (2007). Estimation of sand wave dynamics in the southern North Sea. In J. McKee Smith (Ed.), *Coastal Engineering 2006. Proceedings of the 30th international conference, 3-8 September 2006, San Diego USA.Vol. 3* (pp. 2630-2642). Singapore /London: World Scientific publishing Co. Ltd. (ISBN 13 978-981-270-636-2).

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

Hennings, I., Lurin, B., Vernemmen, C., and Vanhessche, U. (2000). On the behaviour of tidal current directions due to the presence of submarine sand waves. *Marine Geology*, 169:57-68.

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 Hulscher, S. J. M. H. (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*, volume 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 shealf seas. *Continental Shelf Research*, 22(18):2795-2806.

Németh, A. A., Hulscher, S. J. M. H., and Van Damme, R. M. J. (2007). Modelling offshore sand wave evolution. *Continental Shelf Research*, 27:713-728.

Németh, A. A., Hulscher, S. J. M. H., and Van Damme, R. M. J. (2006). Simulating offshore sand waves. *Coastal Engineering*, 53:265-275.

Passchier, S. and Kleinhans, M. G. (2005). Observations of sand waves, megaripples, and hummocks in the Dutch coastal area and their relation to currents and combined flow conditions. *Journal of Geophysical Research - Earth Surface*, 110 (F04S15, doi:10.1029/2004JF000215).

Peregrine, D. H. (1976). *Interaction of water waves and currents, In: Advances in applied mechanics*, volume 16, pages 9-117. New York Academic Press, Inc.

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

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

Van der Meer, F. M., Hulscher, S. J. M. H., Hanes, D. M., and Elias, E. (2007). San Francisco Bay sand waves: modelling and observation. In Dohmen-Janssen, C. M. and Hulscher, S. J. M.H., editors, *River,Coastal and Estuarine Morphodynamics: RCEM 2007*, Taylor & Francis Group, London.

Van der Veen, H. H., Hulscher, S. J. M. H., and Knaapen, M. A. F. (2005). Grain size dependency in the occurrence of sand waves. *Ocean Dynamics*, (DOI 10.1007/s10236-005-0049-7).

Wilkens, J. (1997). Sand waves and possibly related characteristics, report for Alkyon Hydraulic Consultancy and Research.