Exploring the main drivers of sand wave dynamics

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ABSTRACT: Offshore developments, such as the construction wind farms, require detailed predictions of sand wave dynamics. State-of-the-art process-based models have not been able to satisfy this need due to several model limitations and gaps in our understanding of sand wave dynamics. In this study, the influence of tidal and non-tidal currents on sand wave dynamics is investigated. Using the newly developed, highly efficient Delft3D Flexible Mesh model, the local hydrodynamics can be reproduced very well, as shown by a validation using field measurements. Moreover, its efficiency allows for computing multi-year hydrodynamics and bed level changes in reasonable computational efforts, which is unprecedented in sand wave modelling. The results show a significant influence of the non-tidal currents on the sand wave morphology, including periods of sand wave migration opposing the long-term migration direction. Improved understanding of these tidal and non-tidal processes and their effect on the delicate balance of sand wave dynamics is vital for modelling in-situ sand wave dynamics for engineering purposes.

1 INTRODUCTION

All over the world offshore activities have been on a rise over the last decades. With an ever-growing population, the offshore area can fulfil various functions, such as green energy production, for which space on land is lacking. Moreover, with a growing connectedness, through goods, energy and data, a well-maintained infrastructure is needed. However, many sandy, shallow seas around the world, such as the North Sea, are covered with active bed forms (Damen et al., 2018). As a result of their size and dynamic character, tidal sand waves may pose a threat to offshore constructions and navigation channels. Through deformation and migration of these bedforms, cables and pipelines can become exposed and navigational depths can be reduces (Nemeth et al., 2003).

Tidal sand waves are found on shallow seabeds throughout the world. These sand waves have lengths of hundreds of meters, can grow up to 25% of the water depth (Damen et al., 2018) and migrate with speeds up to tens of meters per year (Van der Meijden et al., 2023). Hulscher (1996) used stability analysis to explain their occurrence. She found a delicate system of tide-averaged residual circulation cells, which causes sand wave growth through bed load transport.

To enable construction in sand wave areas, data-driven analyses has been used to provide predictions of future bed levels. In these types of analysis measured sand wave bathymetries are extrapolated into the future, using migration rates from historic data (e.g. Deltares, 2016). However, these extrapolated bathymetries are subject to significant uncertainties. Process-based models could assist in increasing our understanding of the sand wave system and reducing these uncertainties. Furthermore, these types of models could offer solutions for data-scarce areas and give insight into the effect of human interventions and extreme conditions.

Past efforts to numerically simulate the sand waves have resulted in increased understanding of the sand wave system. It was found that residual currents (Nemeth et al., 2002) and superposition of the M4 tidal component (Besio et al., 2003) can cause migration of sand waves. Moreover, Leenders et al. (2021) found a significant influence of underlying tidal sand banks on sand waves, causing upslope migration.

Campmans et al. (2018) studied the influence of wind waves combined with (steady) wind driven currents on sand waves. They found an increased migration rate and a reduced sand wave height due to surface waves.

However, in all long-term modelling studies the equilibrium sand wave height is largely overestimated (e.g. Van den Berg et al., 2012, Van Gerwen et al. 2018), although comparison with the field is complicated due to numerous model simplifications. Krabbendam et al. (2022) were the first to apply a sand wave bathymetry based on measurements in their Delft3D-4 model. Although the migration rates seemed to be well represented, the results showed growing sand waves, while, in reality, they were stable in height. Moreover, the shapes of the sand wave deformed during the simulation, leading to reduced steepness of the lee-side slopes.

These differences between the model results and reality indicate that there are still processes missing in our simulations. A common factor between these and other studies are the simplifications made in the hydrodynamic forcing of the model. In all cases it is assumed that sand wave dynamics are purely caused by the main tidal components (M2 and M4), possibly combined with a constant residual current. However, in the field we often see shape deformations and changes in migration rate over time (see for example Figure 1). This cannot be explained through purely periodic forcing. Moreover, at the Taiwan shoal a substantial influence of a passing tropical storm was found by Bao et al. (2020). They

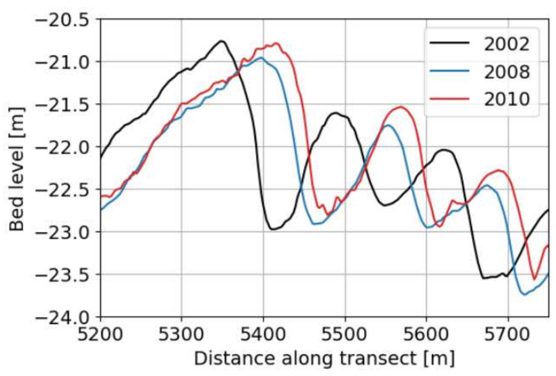

Figure 1. Observed changes in sand wave height and migration rate over time. From MBES data of a transect close to Texel, The Netherlands

discovered height reductions of over a meter (for sand waves with a height of ~15m) and momentarily increased migration rates of the sand waves.

The aim of this paper is to determine the influence of irregular time-varying currents on sand wave dynamics. It is hypothesized that non-tidal currents from hydrodynamic events, such as storms, have a significant influence on the temporal sedimentation and erosion rates, and thereby on sand wave migration and shape.

2 METHODS

To study the influence of time-varying hydrodynamic influences on sand wave dynamics, a Delft3D Flexible Mesh (FM) sand wave model is set up. To allow for validation of the hydrodynamics within the model a location is chosen where Acoustic Doppler Current Profiler (ADCP) measurements are available.

2.1 Study site

The chosen location lies within the Hollandse Kust Zuid (HKZ) offshore wind farm area. In relation to the development of the wind farm, two ADCP buoys were deployed here for a period of two years. At the site location (shown in Figure 2), sand waves are present with a height of around 3 meters and a wavelength between 300 and 700 meters. The mean water depth is 23 meters. The sand waves migrate with 1-2 meters per year towards the north-east.

2.1.1 Measurement data

An ADCP measurement buoy was deployed at the model site from June 2016 until June 2018. The buoy measured among others the current profile over depth and the water level. The current was measured at intervals of 2 meters, between 4 and 20 meters below the surface. Measurements are available at intervals of 10 minutes and are publicly available via RVO (2018)

The current data has high coverage (94%) and showed excellent correlation with a neighbouring buoy (deployed for robustness), see Deltares and Fugro (2018).

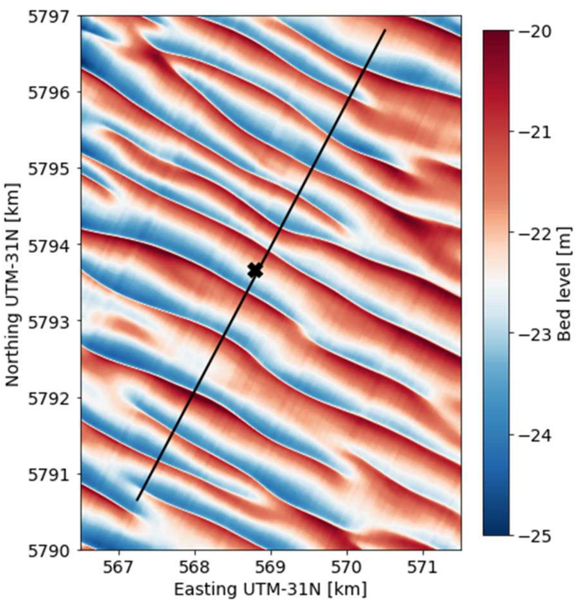

Figure 2. Measured sand wave bathymetry at model location (2016), including sand wave transect in the model indicated by line and the location of the ADCP buoy indicated by the cross.

This data is thus judged to be highly trustworthy.

The measurement device for the water level measurements showed more problems. The device was frequently out of order and thus only has a coverage of 26% of the period. Moreover, significant offsets were observed between the data of the two buoys. The data was corrected for the offset using the large scale DCSM model (see Deltares and Fugro, 2018).

In relation to wind farm development also high resolution Multibeam Echosounder (MBES) bathymetry data was collected. The survey took place in the spring of 2016, which perfectly aligns with the available hydrodynamic data.

2.2 Delft3D Flexible Mesh model

To simulate hydrodynamics, sediment transport and morphology the newly developed Delft3D FM modelling software is used. This model is the successor of the Delft3D-4 model (Lesser et al., 2004), which is established in sand wave modelling (see a.o. Borsje et al., 2014; van Gerwen et al., 2018 and Leenders et al., 2021). The Delft3D FM model offers the possibility to use unstructured grids (flexible meshes) and can run models in parallel (on multiple nodes), contrary to its predecessor. Combined with a time-varying timestep, automatically defined based on the Courant number, the efficiency is increased significantly. For the numerical scheme refence is made to the user manual (Deltares, 2023)

2.3 Sand wave model set-up

The model set-up used in this study is based on the Delft3D-4 model by Borsje et al. (2014). Some alterations had to be made, to make the model suitable for simulating realistic, time-varying hydrodynamics in this study site. In this section the main focus will be on the differences in the set-up.

2.3.1 Model lay-out

To reduce computational effort a 2DV model is set up, limiting the domain to the direction perpendicular to the crest and the vertical (see Figure 2). Since the sand waves are quite regular and long crested in this domain, this simplification is expected to have limited effect on the results. The original domain length from Borsje et al. (2014) is reduced from 50 to 17 km. By bringing the boundaries closer to the area of interest, the hydrodynamics at the boundary are more alike what is present in the sand wave domain. In the middle of the domain a sand wave area of 7 km is present, where the sand waves are dampened over the outermost kilometre. This sand wave bathymetry, composed from measurements, is superimposed on the static bathymetry. At the location of the sand waves, horizontal grid cells of 2 meters are used, which increase in size towards the boundaries, outside of the area of interest. In the vertical 40 sigma layers are used, with increasing size from 0.05% at the bed to 14% at the surface.

2.3.2 Hydrodynamic set-up

The Riemann boundaries in the original model set-up (Borsje et al., 2014, which are developed to simulate tidal conditions, are replaced by one velocity (SW) and one water level (NE) boundary. In this way non-tidal currents can be included, which is not

Table 1: Model cases. Positive velocities indicate flood direction (from left to right in the figures)

Case	I	II	III
Forcing type	M2, M4, Z0	M2, S2, M4, Z0	Complete timeseries
Residual current type	Constant	Constant	Time-varying
Residual current strength [m/s]	+0.026	+0.026	Between -0.40 and +0.74

possible using Riemann boundaries. The timeseries for the boundary conditions are derived from the large scale DCSM model (see Deltares, 2018), which includes tidal flows, meteorological influences and density driven flows. With this model a hindcast is done for the measurement period (June 2016 to June 2018). To allow for comparison of the results in- and excluding non-tidal currents, also purely tidal models are set up (see Table 1). For these models, specific tidal components are filtered out of the current and water level timeseries.

2.3.3 Morphodynamic set-up

For simplicity the morphodynamic parameters are not tuned and purely based on measurement or previous model studies. A single fraction sediment is used, with a log-uniformly distributed grainsize. The median grainsize is chosen as 350 μm based on Deltares (2016). The Chézy bed roughness (C) is taken as 70 $m^{1/2}s^{-1}$ and the bed slope parameter α_{bs} of 3 is applied, following Van Gerwen et al. (2018). Only bed load transport is included in the model, since this is expected to be the dominant transport mode. The bed load transport is calculated following the Van Rijn 2004 transport formula. No morphological scaling is applied, so that the hydrodynamic time equals the morphological time. The first 2 days of the simulation are used as hydrodynamic spin-up, excluding morphological change.

2.3.4 Model cases

To assess the impact of non-tidal currents, three model cases are defined. The cases are listed in Table 1. The Case I model most resembles the state-of-the-art model set-up. Here the M2 tidal component (which causes sand wave growth) is combined with the M4 tidal component and a constant residual current (leading to migration). In Case II the S2 tidal component is added, which generates a spring-neap tidal cycle. The Case III model is forced by a timeseries of the full hydrodynamics (including meteorological influences). All models are run for 2 years. For Case III this period spans June 2016 until June 2018 (coinciding with the ADCP measurements).

3 RESULTS

3.1 Hydrodynamic validation

To assess the quality of the model nesting and the ability of the model to reproduce non-tidal currents and water levels a validation is done between the sand wave model and the ADCP measurements. For this validation the current measurements at a depth of 12 meters below the surface are used, since here the best agreement between the two buoys was found (Fugro and Deltares, 2018). The modelled velocity at this depth is constructed through interpolation. As shown in Figure 3, a good agreement is found between the modelled and measured velocities. The model is well able to reproduce momentary high current velocities. Some outliers are visible, which can be attributed to measurement inaccuracies, and the velocity is slightly overestimated in the sand wave model. A similar comparison between the sand wave model and the large scale DCSM model shows a RMSE of 0.036 m/s, indicating that these errors cannot be reduced much further, while using the DCSM model as nesting host.

The modelled and measured water level show good agreement (see Figure 3). Since there were some technical issues with the water level measurements only the first 4.5 months of measurements at the end of 2016 are used for the comparison here. After a long

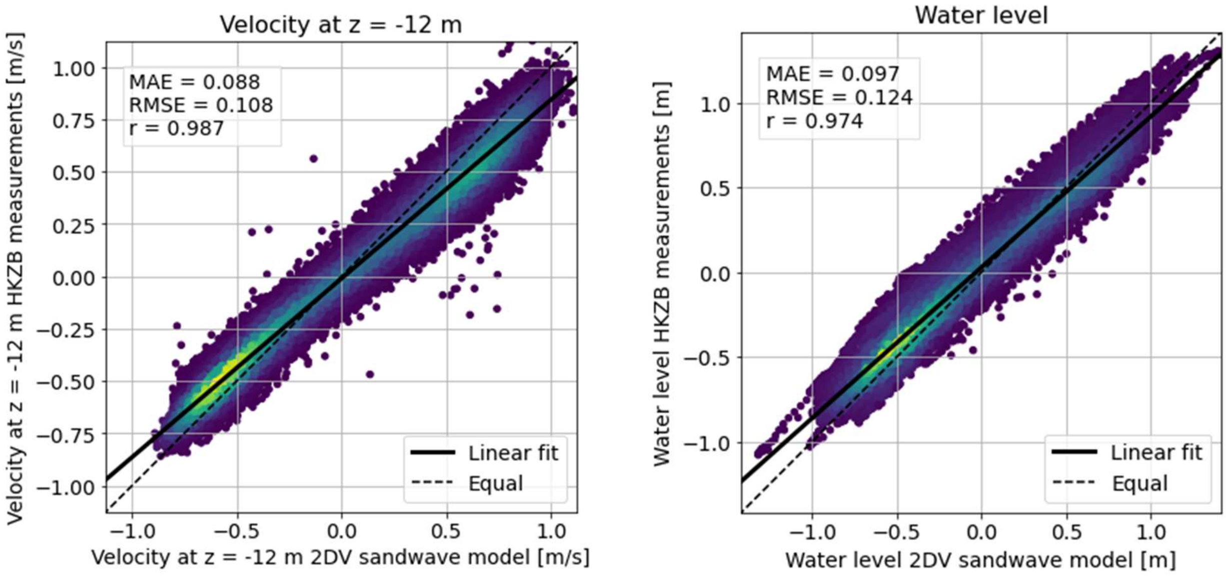

Figure 3. Validation of the modelled current velocities (left) and water levels (right), from the Case III sand wave model with the ADCP measurements.

interception, the last 1.5 months of measurements in 2018 showed a large absolute offset, probably caused by incorrect referencing. The model shows a slight overestimation of the water level variations, but otherwise a nice match is found. Again, with a 0.02 m RMSE between the sand wave model and the DCSM model, not much room for improvement is left.

3.2 Morphodynamic results

The morphodynamic development of the sand waves clearly shows the influence of time variations in the current velocities. In the more traditional model set-up in Case I we see a steady pattern of erosion at the crest of the sand wave and deposition at the steep lee slope. This indicates migration of the sand wave in flood direction. Since every tide is the same with this type of forcing (M2, M4 and Z0), the sedimentation and erosion patterns stay the same throughout the run.

When we add the S2 tidal component in Case II we see more variation in the sedimentation and erosion patterns due to the creation of a spring-neap tidal cycle. During neap tides the bed is quite stable, while during spring type significant migration is occurring.

Lastly the full forcing model shows a very scattered pattern, where spring-neap tidal cycle can still be distinguished in the results, but the rates differ significantly between consecutive days. Events can cause large instantaneous migration. At other times, a sedimentation-erosion pattern indicating migration opposite to the long-term migration direction can be distinguished. This can be recognized by the erosion of the lee-side slope. The tide averaged sedimentation and erosion rates during these events can easily be 4-8 times higher than what is found using a simple tidal forcing (Case I). The different periods in the model showed similar results, with a highly chaotic character.

4 DISCUSSION

In this research we have improved the model set-up of the state-of-the-art sand wave model and shown the importance of non-tidal current for sand wave dynamics. By applying a different kind of boundary conditions more realistic hydrodynamics could be included in the model and the accuracy of both tidal and non-tidal hydrodynamics was improved. The switch to the Delft3D FM modelling software increased the efficiency of the model significantly. This offers the possibility to run years of hydro- and morpho-dynamics in a 2DV sand wave model in just a few days (without using a morphological scale factor; i.e. morfac). The morphological results show a large influence of the time-varying hydrodynamics on sand wave migration.

Periods with sedimentation-erosion pattern indicating opposite migration are observed.

One limitation of this study is the exclusion of free surface waves. Waves can influence sand waves even at large water depths. Campmans et al. (2018) found that especially extreme waves have a significant influence on sand wave migration, even with a low probability of occurrence. The hydrodynamic events present in the Case III model would, in reality, largely coincide with the periods of intense wave action. In this way the sedimentation-erosion pattern leading to migration caused by these wind-driven currents are amplified and the patterns will be even more stochastic.

Due to the 2DV set-up of the model, currents with an angle of incidence with respect to the sand waves were only included with their component in the along transect direction. Although sediment transport along the crests will not directly lead to sand wave migration, these currents may well help in reaching the sediment transport threshold. Moreover, in sand wave fields with more variation in the bathymetry this along crest direction cannot be left out of consideration.

The morphological parameters used in this study were not calibrated. They are purely based on recent papers and field measurements. These parameters are not expected to have a significant effect on the qualitative results of this study, although the magnitude of the sedimentation and erosion could differ. The scattered pattern of sedimentation and erosion caused by the non-tidal currents will still be present and may even be amplified through different morphological parameters (e.g. when the threshold for sediment transport is changed).

In the model including full forcing, sedimentation-erosion pattern indicating migration in both ebb and flood direction were found. To a certain extent, these effects cancel out on longer time periods. In some areas, with storm events from both directions, with similar magnitudes, a constant residual current may thus be an acceptable approximation. However, especially when large events are present, such as the tropical storm in the study by Bao et al. (2021), these specific events may not be neglected. In these areas one storm can transport more sediment than an entire year of tidal forcing. These events thus lead to a certain stochasticity, which should be considered when predicting future bed levels in sand wave areas. The same holds for areas where tidal currents are close to the critical current for sediment transport. Here the ability of the tides to cause migration and deformation of sand waves is limited, increasing the importance of specific events.

5 CONCLUSIONS

This research shows the delicacy of the sand wave system. Relatively small changes in hydrodynamic forcing can have a large influence on sand wave dynamics. We should thus be careful when trying to predict the dynamics of sand wave fields using simplified models.

As a next step the morphodynamic results of the model can be validated using field measurements. Since there are no measurements available for the simulation period used in this study, this is not an option here. By running the simulation for the period between two bathymetry measurements, the need for calibration of the morphological parameters can be determined. With a calibrated model, more accurate predictions of sand wave migration and deformation can be realized using process-based models. Moreover, these models can give insight into uncertainties in predictions related to extreme events.

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