Modelling the past evolution of observed tidal sand waves: the role of boundary conditions

Janneke M. Krabbendam *Utrecht University, Utrecht and WaterProof B.V., Lelystad, the Netherlands – j.m.krabbendam@uu.nl*
Abdel Nnafie *Utrecht University, Utrecht, the Netherlands – A.Nnafie@uu.nl*
Luitze M. Perk *WaterProof B.V., Lelystad, the Netherlands – luitze.perk@waterproofbv.nl*
Bas W. Borsje *University of Twente, Enschede, the Netherlands – b.w.borsje@utwente.nl*
Huib E. de Swart *Utrecht University, Utrecht, the Netherlands – H.E.deSwart@uu.nl*

ABSTRACT: Tidal sand waves are rhythmic bed forms located in many coastal seas. These bed forms have heights up to ten meters and migration rates of several meters per year. Due to their dynamic nature, sand waves can uncover buried cables and pipelines, thereby making them subject to risk of damage. This study aims at developing a new numerical 2DV model (Delft3D) to simulate the past evolution of tidal sand waves on a decadal timescale (hindcast study). In particular, the effect of imposing different types of boundary conditions (time series of currents, water levels and Riemann invariants) on sand wave evolution is investigated. Simulations are conducted for a period of ten years, whereby an observed sand wave field is used as an initial bathymetry. Model results show that imposing time series of Riemann invariants at one boundary and of water level at the other yields the best agreement with bed level observations.

1 INTRODUCTION

Coastal seas are often characterized by the presence of a large variety of rhythmic bed forms with different spatial and temporal scales (Van Dijk et al., 2008). One type of these bed forms are tidal sand waves, which have wavelengths of 100-1000 m, heights of 1-10 m and migration speeds of up to 10 m/year (McCave, 1971).

Because of their dynamic behaviour, variations in the characteristics of sand waves (e.g. crest height, trough depth, migration rate) pose a hazard to offshore activities, for example by uncovering originally buried cables and pipelines, by changing the depth of navigation channels and scouring offshore platforms (Németh et al., 2003). Therefore, increasing knowledge of the dynamics of sand waves could lower costs related to these offshore activities, e.g. by optimizing burial depths of cables and pipelines.

Currently, when planning the burial of cables and pipelines, predictions of sea bed evolution are used that result from extrapolation of historical trends. As this method has large uncertainties, alternative predictions are needed. Process-based models are suitable tools for such a purpose, as they contain the physical processes driving tidal sand wave evolution.

Various modelling studies have been conducted over the past and these can be divided into linear and non-linear models. The first models used linear stability analysis to study the initial formation of tidal sand waves (see Besio et al. 2008 for an overview). In these studies it was shown that the interaction of the oscillating tidal flow with a small amplitude wavy bottom results in residual circulation cells in the vertical plane. Because of the higher instantaneous velocity up the crest and the non-linear relation between sand transport and velocity, the sand transport is always higher up the crest than down. This results in a net convergence of sand at the crest when averaged over a tidal cycle. This growth process is counteracted by the divergence of slope-induced transport. Borsje et al. (2013) used a complex numerical model (Delft3D) to investigate the initial formation. However, linear stability analysis is only valid for sand waves with small amplitudes.

Non-linear effects cause the growth rate to slow down and need to be included in order to study long-term evolution of tidal sand waves. Idealized non-linear models, such as the one presented by Campmans et al. (2018 and references therein), showed promising results, but sand wave amplitudes tended to grow larger than observed. Van Gerwen et al. (2018) analysed the model of Borsje et al. (2013) for longer timescales and sand waves were able to grow from an initial perturbation to an equilibrium height. However, the only initial states considered in these studies were sinusoidal sand waves with small amplitudes. In order to simulate the evolution of observed sand waves, sand waves with a finite height should be used as initial state.

The aim of this study is to develop a new numerical model based on the modelling system Delft3D that is able to simulate the past evolution of observed tidal sand waves, i.e. a hindcast study. In particular, the effect of imposing different types of boundary conditions on sand wave evolution is investigated. To this end, simulations are conducted for a period of ten years, whereby an observed sand wave field is used as an initial bathymetry. The simulated bed level after ten years is compared with observations. Comparison between model results and observations includes sand wave height, wavelength, shape and migration rate.

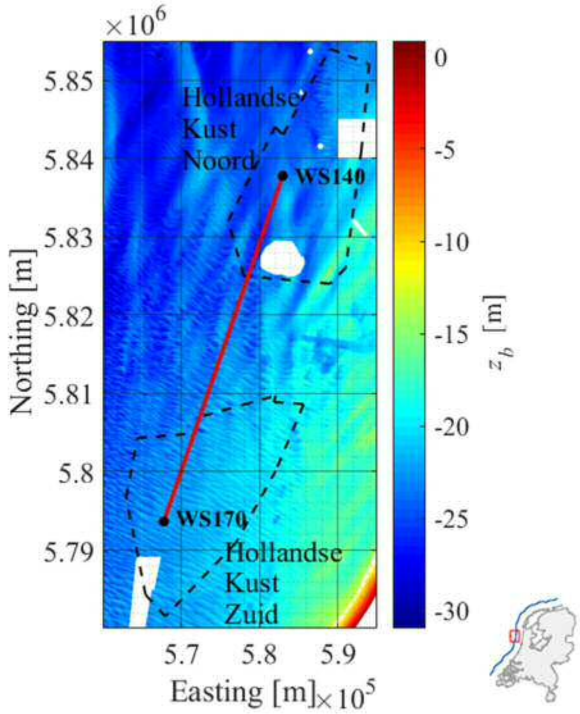

Figure 1. Bed level z_b of 2010 (Netherlands Hydrographic Office, 2017) and location of future wind farms Hollandse Kust Zuid and Noord. The red line corresponds to the transect under investigation.

2 MATERIAL AND METHODS

Study area

The study area consists of a 45.5 km transect located between two measuring buoys (WS170 and WS140) in the North Sea (Fugro, 2018a and b). The first buoy is located in the area of the future wind park Hollandse Kust Zuid (HKZ) and the second in Hollandse Kust Noord (HKN), as shown in Figure 1. In this area, bathymetrical surveys were performed by the Netherlands Hydrographic Office of the Royal Netherlands Navy (2017).

Model description

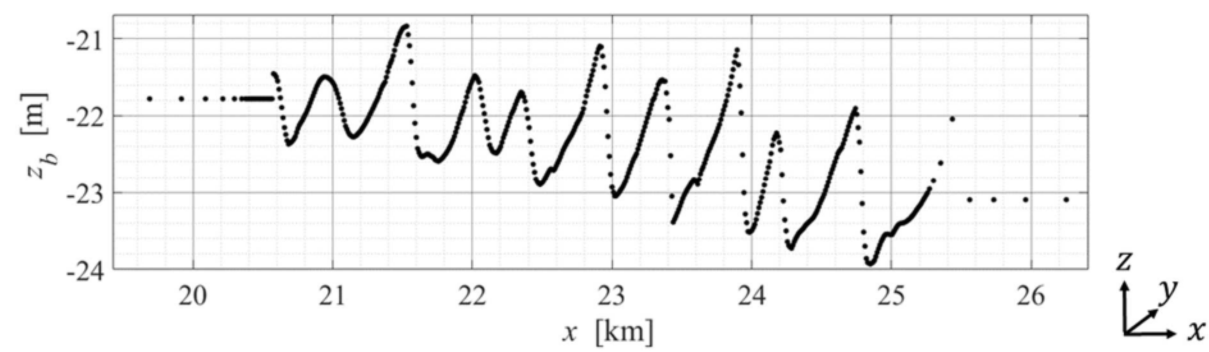

Figure 2. The initial bed level z_b (t=0) (Netherlands Hydrographic Office, 2017) over x, which is the distance from boundary point WS170 in the HKZ area. Figure is a close-up of the middle of the domain where the sand waves under investigation are located.

The formation of sand waves is modelled using the numerical shallow water model Delft3D-FLOW (Lesser et al., 2004). It consists of a horizontal momentum equation, a continuity equation, a bed load and suspended load transport equation and a sediment continuity equation. The model equations are solved by applying sigma layering in the vertical direction. In this study, the model is run in the 2DV mode, i.e. considering flow and variation in the x- and z-direction only, while assuming zero flow and uniformity in the y-direction. This is valid as the crests and the migration are oriented perpendicular to the direction of the principal tidal current. The x-coordinate is defined as distance from boundary point WS170 in the HKZ area. For turbulence closure the $k-\varepsilon$ model is chosen.

In order to study the evolution of observed sand waves, bathymetric data as measured in 2000 (Netherlands Hydrographic Office, 2017) along the transect in Figure 1 were used as initial bed level. To minimize boundary effects, only the sand waves in the middle 5 km of the domain were retained (Fig. 2).

The tidal flow was forced with a three-month time series of water level and depth-averaged velocity measured by the two buoys (Fugro, 2018a and b). A snapshot of this data as measured in HKZ (WS170) is shown in Figure 3, with depth-averaged velocity U in blue and the water level ζ in red. These time series were imposed in four different ways: (1) $U(t)$ and $\zeta(t)$ combined into two Riemann invariants $R(t)$ at both boundaries; (2) $U(t)$ at the Southern boundary ($x=0$) and $\zeta(t)$ at the Northern boundary ($x=L_x$); (3) a water level time series $\zeta(t)$ at both boundaries and (4) a Riemann invariant $R(t)$ at $x=0$ (S) and $\zeta(t)$ at $x=L_x$ (N). The Riemann invariants, which are constant along the characteristic curves of the system of equations, are implemented by combining water level and velocity timeseries as follows (Deltares, 2013):

$$R(t)=U(t)+\zeta(t)\sqrt{\frac{g}{d(t)}}\,. \qquad (1)$$

The median sand grain size d_{50} was set to 0.25 mm (Fugro, 2016). The bed slope factor α_{bs} is a correction parameter and is included to account for the fact that sand is transported more easily downhill than uphill. The value of α_{bs} was set to 3, which corresponds to an angle of repose of sand of 19°. The Chézy roughness C was set to 75 $m^{1/2}\,s^{-1}$ after Van Gerwen et al. (2018).

The horizontal grid spacing varies from $\Delta x=1500$ m at the boundaries to $\Delta x=10$ m in the area of the sand waves (Fig. 2). In the vertical direction, the domain is divided into 50 σ-layers in such a way that the vertical resolution is highest near the bed and decreases towards the surface. To speed up the computation time, a morphological acceleration factor (MF) of 100 was intro-

Table 1: Model parameters

Parameter	Symbol	Value
Horizontal domain length	L_x	45.5 km
Chézy roughness	C	75 $m^{1/2}$ s^{-1}
Median sand grain size	d_{50}	0.25 mm
Bed slope parameter	α_{bs}	3
Hydrodynamic time step	Δt	6 s
Horizontal grid spacing	Δx	10-1500 m
No of sigma layers	-	50
Morphological acceleration factor	MF	100

duced. The hydrodynamic time step was set to $\Delta t = 6$ s. The hydrodynamic runtime was 10 years in order to compare the output with

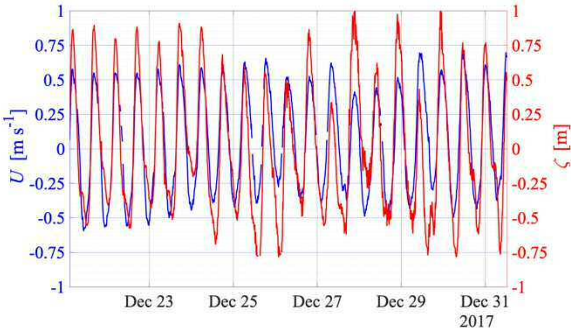

Figure 3. Snapshot of time series of depth-averaged velocity U (blue) and water level ζ (red) over time (Fugro, 2018a), measured at HKZ (WS170).

the bathymetry data of 2010. An overview of the main model parameters and their values is provided in Table 1.

3 RESULTS AND DISCUSSION

From Figure 4, which shows the observed bed levels in 2000 and 2010 (black and blue

lines, respectively), it appears that sand waves migrate in the positive x-direction, at rates ranging between 0.5 m/year and 2 m/year. Two sand waves have not migrated in this period (indicated by black arrows in Figure 3), but they underwent changes in their shape. Most of the sand waves retained their trough depth over the period 2000-2010, but their crest height decreased in some locations and increased in others.

Figure 5 shows the simulated bed levels z_b for different cases of boundary conditions (a), as well as bed level differences Δz_b with respect to observations of the bed level in 2010 (b). From this figure, it turns out that simulated bed levels are rather sensitive to the type of boundary conditions imposed. Best agreement between model results and observations is obtained in the case of using a time series of Riemann invariants $R(t)$ at both boundaries (Case 1 in Table 2) and in case of using $R(t)$ at the Southern boundary and $\zeta(t)$ at the Northern boundary (Case 4). In these cases, the simulated sand crest heights and trough depths agree well with observations, although the model over (under)-predicts crest height at some locations. The simulated sand wave field migrates in the same directions as the observed field. In the other cases (Cases 2 and 3), the simulated sand wave field migrates in the opposite direction compared to observations, and its shape is considerably different from the one observed, particularly in Case 3. The achievement of best model performance in Cases 1 and 4 is also

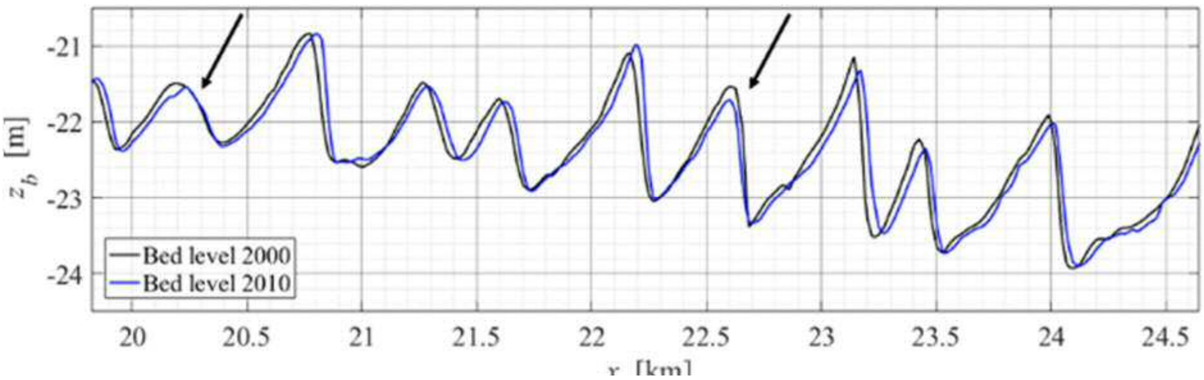

Figure 4. Observed bed level of **2000** and the observed bed level of **2010**. Figure is a zoom-in of the transect.

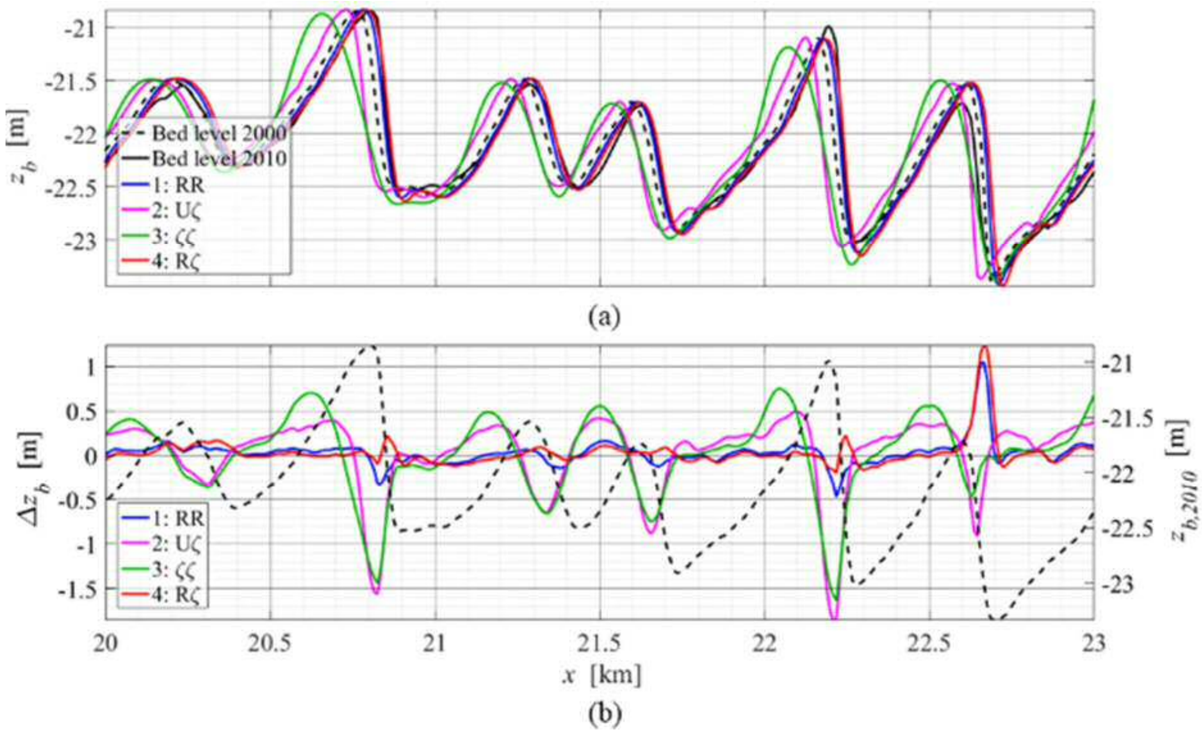

Figure 5. (a) Bed level z_b measured in 2000 and 2010 (dashed and solid black lines, respectively) over x, and simulated z_b for the different types of boundary conditions: 1. two Riemann invariants $R(t)$ (blue); 2. depth-averaged velocity $U(t)$ and water level $\zeta(t)$ (magenta); 3. two water level time series $\zeta(t)$ (green); 4. Riemann invariants $R(t)$ and water level $\zeta(t)$ (red). (b) Difference between modelled and measured bed level Δz_b for different sets of boundary conditions. The right y-axis corresponds to bed level as measured in 2010 ($z_{b,2010}$) (black dotted line).

confirmed by the smallest root-mean-square-error (RMSE), compared with other cases (Table 2).

Sand wave migration is caused by differences in ebb- and flood velocity and/or duration (Besio et al. 2008). These differences can arise from the presence of a residual current (M_0) or the phase difference between the principal tidal component M_2 and its first overtide M_4. The results in Figure 5 demonstrate that the type of boundary conditions imposed significantly affects the migration rate. This is surprising, as these boundary conditions are based on the same time series, meaning that residual currents and the phase difference between M_2 and M_4 should be the same. Apparently, different types of boundary conditions translate into different residual velocity fields and can therefore result in opposing migration directions.

Table 2 Root mean square error

	Boundary conditions	RMSE (m)
1	S: $R(t)$ and N: $R(t)$	0.15
2	S: $U(t)$ and N: $\zeta(t)$	0.48
3	S: $\zeta(t)$ and N: $\zeta(t)$	0.46
4	S: $R(t)$ and N: $\zeta(t)$	0.14

There are several model limitations. Firstly, one horizontal dimension is neglected, while sand waves are in fact a 3D phenomenon (see for example Figure 1). Also, a morphological acceleration factor is introduced, which is convenient for the computation time, but can cause errors. Thirdly, the effects of wind driven currents and waves are neglected (Campmans et al. 2018). Furthermore, the median grain size is assumed to be constant throughout the whole domain, while measurements by Fugro (2016) and surveys elsewhere in the North Sea (see e.g. Van Oyen and Blondeaux (2009) and references therein) indicate that sorting patterns occur along sand waves. Including these sorting patterns might affect the magnitude and direction of sand transport. Finally, this model was only tested for one location and it is a topic of future research to apply it to other places in the North Sea.

4 CONCLUSIONS

The model results are rather sensitive to the type of boundary conditions imposed; especially the migration rate is affected by changing the boundary conditions. The best agreement between the observed and simulated bathymetry results from a combination of a time series of Riemann invariants and of water levels. Using the latter, the model is able to mimic the evolution of mature sand waves in the HKZ-HKN area in the North Sea and can therefore provide a valuable tool in the planning of cable burial depths provided that velocity and/or water level measurements are available.

5 ACKNOWLEDGEMENT

This research is part of NWO project NWA.ID.17.038 of the Netherlands Organisation of Scientific Research.

6 REFERENCES

Besio, G., Blondeaux, P., Brocchini, M., Hulscher, S. J. M. H., Idier, D., Knaapen, M. A., Németh., A. A., Roos, P. C., Vittori, G. 2008. The morphodynamics of tidal sand waves: A model overview. Coastal Engineering, 55(7-8), 657–670.

Blondeaux, P., Vittori, G. 2016. A model to predict the migration of sand waves in shallow tidal seas. Continental Shelf Research, 112, 31-45.

Borsje, B. W., Roos, P. C., Kranenburg, W. M., Hulscher, S. J. M. H. (2014). Modeling tidal sand wave formation in a numerical shallow water model: The role of turbulence formulation. Continental Shelf Research, 60, 17–27.

Campmans, G., Roos, P. C, , de Vriend, H. J., Hulscher, S. M. J. H. , 2018. The influence of storms on sand wave evolution: a nonlinear idealized modelling approach. Journal of Geophysical Research: Earth Surface. doi:10.1029/2018jf004616.

Deltares, 2013. User manual Delft-3D FLOW. Technical report. Deltares, Delft.

Fugro, 2016. Geophysical Site Investigation Survey, Wind Farm Site I. Technical Report. Fugro, Leidschendam.

Fugro., 2018a. HKN Metocean Campaign Data & Reports. Retrieved from https://offshorewind.rvo.nl/windwaternh

Fugro., 2018b. HKZ Metocean Campaign Data & Reports. Retrieved from https://offshorewind.rvo.nl/windwaterzh

Lesser, G., Roelvink, J. v., Van Kester, J., Stelling, G., 2004. Development and validation of a three-dimensional morphological model. Coastal Engineering, 51(8-9), 883–915.

McCave, I. N., 1971. Sand waves in the North Sea off the coast of Holland. Marine Geology, 10(3), 199–225.

Németh, A. A., Hulscher, S. J. M. H., De Vriend, H. J., 2003. Offshore sand wave dynamics, engineering problems and future solutions. Pipeline and Gas Journal, 230(4), 67–69.

Netherlands Hydrographic Office., 2017. Hydrographic surveys. Retrieved from http://opendap.deltares.nl/thredds/catalog/opendap/hydrografie/surveys/catalog.html

Van Dijk, T. A. G. P., Lindenbergh, R. C., Egberts, P. J. P., 2008. Separating bathymetric data representing multiscale rhythmic bed forms: A geostatistical and spectral method compared. J. of Geophys. Res.: Earth Surface, 113(4), 1– 16.

Van Gerwen, W., Borsje, B. W., Damveld, J. H., Hulscher, S. J. M. H., 2018. Modelling the effect of suspended load transport and tidal asymmetry on the equilibrium tidal sand wave height. Coastal Engineering, 136, 56–64.

Van Oyen, T., Blondeaux, P., 2009. Grain sorting effects on the formation of tidal sand waves. Journal of Fluid Mechanics, 629, 311–342.