Episodical sand wave migration: analysis of high temporal resolution bathymetry

J.H. Damveld *University of Twente, Enschede, Netherlands – j.h.damveld@utwente.nl*
R. van der Meijden *University of Twente, Enschede, Netherlands*
B.W. Borsje *University of Twente, Enschede, Netherlands*
S.J.M.H. Hulscher *University of Twente, Enschede, Netherlands*

ABSTRACT: In this work we present the analysis of a dataset containing high temporal and spatial bathymetric data. The data consists of several survey lines, of which a spatial overlap of around 30 meters can be used the determine sand wave migration. The interval between the survey lines varies between days and months. A lowpass filter is applied to the raw data to separate the superimposed megaripples from the sand waves, and subsequently the peaks have been determined by calculating the peak prominence. Overall the data shows a low average migration rate, but locally high variations are observed. Moreover, bidirectional migration is visible on the slopes of sand banks. The high spatial resolution also reveals the presence of megaripples on practically all stoss slopes of the sand waves, in contrast to the smooth lee slopes. Altogether, this dataset shows the unique potential for analysing the episodical nature sand wave migration.

1 INTRODUCTION

The seabed of coastal shelf seas, such as the North Sea, consist of various rhythmic bed patterns (Figure 1). Sand banks, oriented parallel to the main tidal current, have spacings of kilometres and heights of tens of metres. Sand waves, oriented perpendicular to the tidal current, are smaller with spacings of hundreds of meters and heights up to 10 metres. In particular these sand waves are relevant for offshore engineering as, on average, they migrate several metres per year (van der Meijden et al, 2023), thereby exposing cables/pipelines and other objects on the seafloor. It is therefore essential to understand their dynamic behaviour in order to realistically predict the dimensions and migration rates of sand waves.

The migration of sand waves is usually determined by measuring the horizontal displacement taken from seabed surveys. However, as these surveys generally have intervals of several years, short-term variability, triggered by e.g. storm events, is not captured in the data. In the scarcely available data that have a high temporal

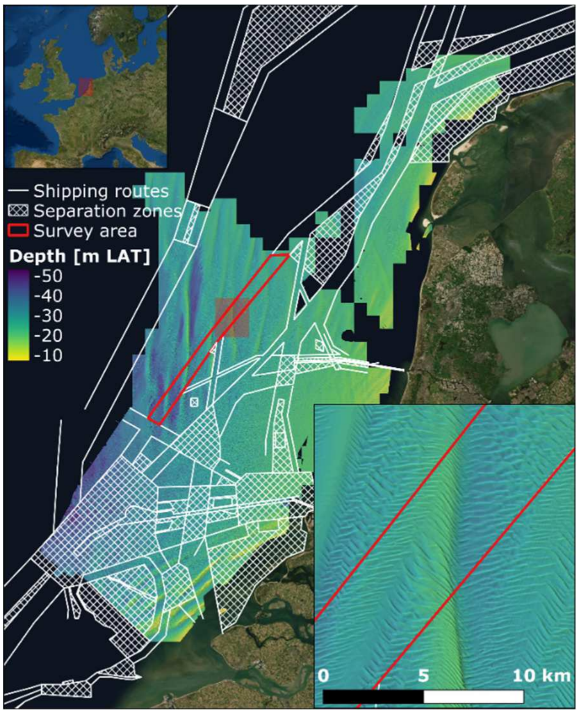

Figure 1. Bathymetric chart showing sand waves and sand banks of the Netherlands Continental Shelf. Data from the Dutch Hydrographic Service.

resolution (e.g. van Dijk et al, 2005), striking nonlinear effects (negative migration, shape changes, flattening) are observed after storms. In an effort to quantify the role of wind and wave processes on sand wave migration, Campmans et al (2018) developed a nonlinear sand wave model containing many important wave-related processes. They found that wind and waves may enhance sand wave migration and its temporal variability. However, they focussed on the long-term (annual – decadal) effects on sand wave migration. Hence, the effect of episodical events on the short-term variability of the seabed remains unclear.

In order to quantify this effect, there is a need for high quality bathymetric data, with a temporal resolution on the order of weeks to match the timescale of these episodical events. At the same time, the spatial resolution must be sufficiently high to allow for migration to be measured, as this can be expected to be on the order of meters between surveys. For practical reasons, seabed surveys (see e.g. the surveyed shipping lane in Figure 1) usually span over a long period of time. It is common practise to average the collected data (survey lines) to a single bathymetric map with a single timestamp, such that seabed changes within that period of time are lost. Analysis of this raw, non-averaged, data can thus reveal the seabed dynamics we are interested in.

Recently, the Dutch Hydrographic Service completed a survey of a shipping lane in the North Sea. As the total survey spans over more than half a year with varying intervals, this dataset is perfectly suited to analyse the episodical nature of sand wave migration. In this work, we aim to highlight the unique potential of this dataset. To this end, we will use the first and last survey lines as they can be expected to show the highest variations in migration. In our analysis we will further relate the dynamics of sand waves to bed forms of both larger (sand banks) and smaller (megaripples) spatial scale.

2 DATA AND METHODS

2.1 Location and survey data

The analysis in this work focusses on a shipping lane in the southern North Sea, roughly 75 km off the coast of the Netherlands (Figure 1). The total survey area is 90 km long and 4 km wide. The average depth in the area in 30 metres, but large variations are observed due to the presence of several sand banks, such as the Brown Bank.

The data has been collected by the Dutch Hydrographic Service using the vessel HNLMS *Luymes*, equipped with multibeam echosounder (MBES), measuring with a resolution of 1 m. The total time span of the survey is around 9 months (09/04/2021 – 16/01/2022), divided into 24 different survey days. Each day represents a single survey line within the dataset. In particular the spatial overlap between the survey lines is of interest as they can be used to reveal the seabed dynamics. Of the potential areas of overlap, 12 lines have an overlap of only a few days, 7 lines have an overlap of a few weeks and 9 lines have an overlap of at least 2 months.

For this work we focus on the overlap of day 4 (01/06-2021) and day 23 (15/01-2022), representing an interval of 7.5 months. Figure 2 shows a zoom the two survey lines, including the overlap, and the profile (red line) along which the data has been extracted. The overlap is around 20 to 30 metres wide, such that there is only a small part of the data left for the analysis, and , hence, only a 2D analysis can be performed.

2.2 Postprocessing of profile data

Several postprocessing steps have been taken before the data was ready for the analysis. Below these steps are explained.

2.2.1 Regridding

The data has been regridded twice. The first is to a resolution of 10 m (as in Figure 2), merely for supporting the operation of the heavy dataset (25 GB per survey line). This subset was used to determine the overlap and

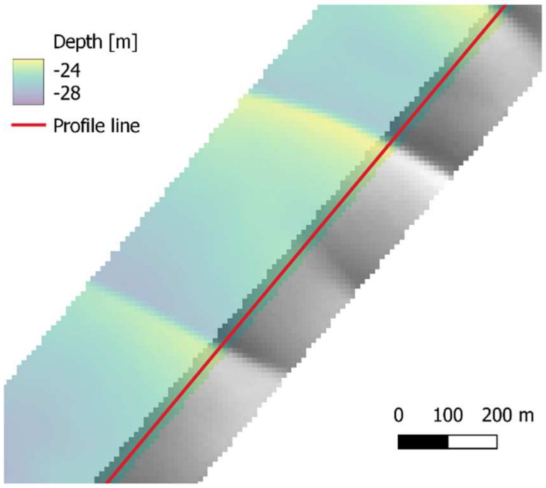

Figure 2. Two survey lines, with one survey line depicted using a grey colour scale. The overlap is visible from the transparency of both layers.

to acquire the coordinates of the profile line. The second is to a resolution of 1 m, since the data along the profile line had a varying resolution due to the slightly varying orientation of the survey area. The constant resolution was needed for the correct application of the lowpass filter. Moreover, some datapoints were missing as at some locations the profile line did not fully overlap with the survey lines.

2.2.2 Separating megaripples

Analogous to van Dijk et al (2008), we applied a lowpass filter to separate superimposed megaripples from the sand waves. Hereto, the sand wave signal is described as a Fourier series, where the resulting (groups of) frequencies (i.e. wavenumbers) can be attributed to a different bed form type. We have used a cut-off frequency of 40 metres to separate the signal, meaning that only bedforms of higher wavelength are used in the analysis of sand wave migration.

2.2.3 Determination of peaks

For the current analysis, we have chosen to apply the tracking of sand wave crests for the determination of sand wave migration. To determine the peaks in the dataset, we applied the *findpeaks* function from the Matlab 2023 Signal Processing Toolbox. It uses the concept of peak prominence, which measures the intrinsic height and location relative to the surrounding peaks. This method yielded a slightly different number of peaks for both survey lines due to some peaks not meeting the minimum prominence value of 1 m. Hence, subsequently all peaks in both survey lines were matched to their counterpart, and orphan peaks were deleted.

3 RESULTS

Both profiles are shown in Figure 3a, including their selected peaks. A zoom of the area is given in Figure 4, clearly displaying the dynamics of the seabed profile. The migration (horizontal displacement) of the peaks is shown in Figure 3b. It appears that locally relatively high migration rates are visible, and that there is no clear trend in direction visible along the survey area. The average migration for the whole area is 0.5 m/year, with a standard deviation of 9 m/year, which is again a clear indication of the high variation in migration over the area.

Compared to literature, the absolute migration rates at some locations are high. This is supported by the shape of the sand waves (see Figure 4), which are highly asymmetrical, indicating migration in the direction of the steep slope. However, the high migration rates may also arise from the presence of lower frequencies that are not fully filtered out, which can be attributed to superimposed megaripples. As can be see from the first peak in Figure 4, the peak detection suggests migration in negative x-direction, whereas the remainder of the profile indicates the opposite. This clearly shows that the migration detection for this particular sand wave is subject to the method and should be treated carefully. This will be further discussed in Section 4.

Although no overall trend in migration direction is visible from the data in Figure 3b, there is a relation visible with larger-scale bathymetry. Here, the black line denotes the smoothed bed profile of the area, of which the local slope is calculated for the peak locations. To highlight this relation, these

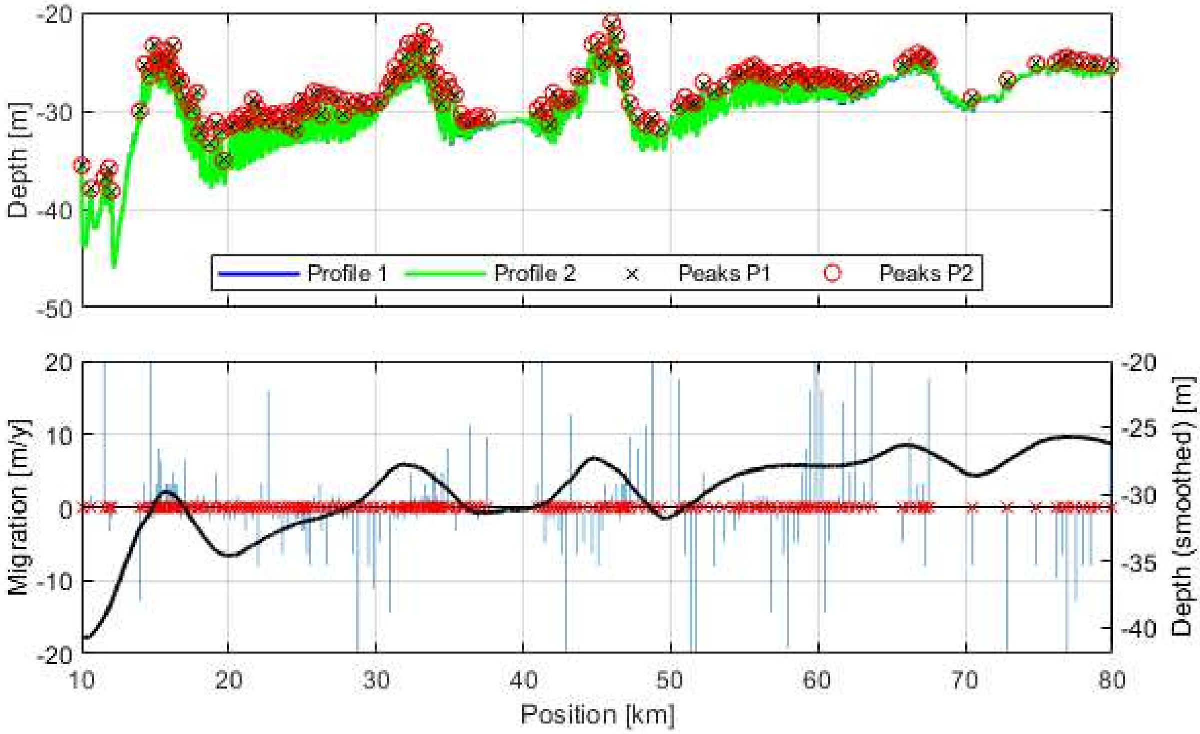

Figure 3. Top: Analysed profile line with their selected peaks. Bottom: the bars denote the migration (horizontal displacement) of the peaks. The red crosses denote all peaks, as some of the peaks did not display any migration. The black line is the smoothed profile used to isolate the underlying topography.

slopes are plotted as a function of the migration rates of the peaks. Although there is a large scatter present in the data, a negative relation is visible between background slope and migration. This observation is related to the bidirectional migration over sand waves (e.g. Zhou et al, 2021, van der Meijden et al, 2023). Note that in this 2D analysis this appears to be migration towards the sand bank crest, whereas from 3D analysis this is known to be more oblique to the sand bank crest.

4 DISCUSSION

We have presented a unique dataset containing bathymetric data of high resolution in both time and space. Such a dataset allows for analysis of the episodical nature of sand wave migration, caused by e.g.

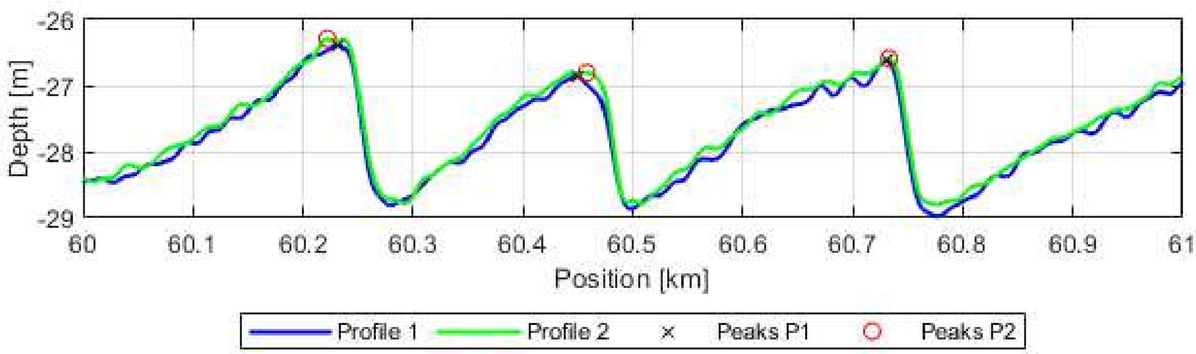

Figure 4. Zoom of figure 3a, clearly showing sand wave both profiles and their peaks.

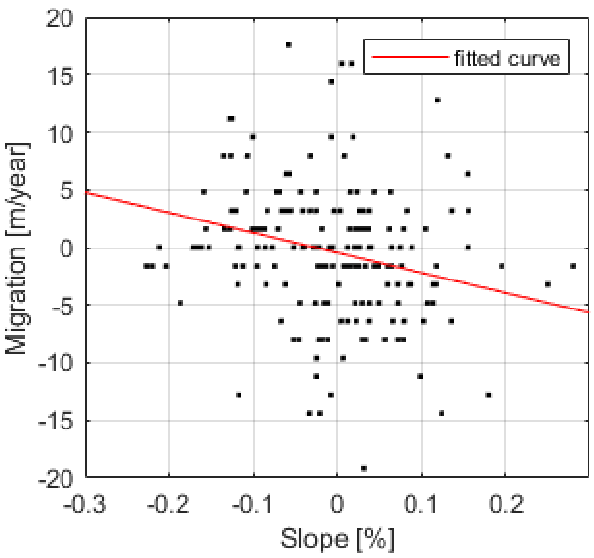

Figure 5. Slope of background topography versus sand wave migration.

storm events. In this work the two surveys lines with the largest temporal overlap have been used, and they clearly show the dynamics of the seabed. Even on such a short interval the migration rates are significant, highlighting the need for high temporal analysis.

No clear trend in migration direction and rate could be determined along the profile. However, the high variation of these indicators suggests that the migration is (partly) caused by an infrequent (strength, location, duration) forcing mechanism. Further analysis of data with smaller temporal overlap, and correlating these results to local wave data should reveal the actual cause for these dynamics. Another indicator which should also be analysed is the shape of the sand wave, which is know to be influenced by storms (van Dijk et al, 2005). For this at least the troughs locations should be determined as well, although a combination with a spatial cross correlation method (e.g. Duffy and Hughes-Clarke (2005)) may yield even better results, as the whole profile is used in the analysis.

Another advantage of using spatial cross correlation, is that the effects of noise from smaller scale bed forms, such as megaripples, may be suppressed. As shown in Figure 4, the presence of smaller features on top of the sand wave may influence the detection of the crest in a negative manner. Using a higher cut-off frequency in the Fourier analysis does not lead to improved results, and may even affect the frequency on which sand waves appear. Other methods that have been tested are a Butterworth filter (see also van Dijk et al, 2008) and fitting a higher order polyline through the data. All these methods did not lead to improved results. Another potential improvement could be to apply these filters on subsets of the data, where the subsets would be selected based on sand waves of comparable morphometric properties, similar to the procedure in van der Meijden et al (2023). Especially in case of analysing the survey lines with shorter time intervals, it is required to decrease the error margin in the methodology as much as possible, as the expected migration rates will also decrease.

The potential presence of superimposed ripples on sand waves is something which is widely known, and has been discussed in literature on multiple occasions (e.g. van Dijk et al, 2005, Damveld et al, 2018). The latter even highlighted the spatial dependence of these megaripples over sand waves, although this was only for a single sand wave and they focussed only on crest versus trough. In the data presented in this work these megaripples are shown to be present on a much wider scale, i.e. on nearly all sand waves in the 280 km^2 survey area. In particular, they consistently occur on the stoss slope, whereas the lee slope is much smoother. As pointed out by Damveld et al (2018), it is important to include such insights in morphodynamic models predicting sand wave dynamics, as these imply a strong spatially varying form roughness, which, in turn, will significantly affect sediment transport predictions. Supporting this statement on a much wider spatial scale, this work once again highlights the need for including spatially varying roughness elements in sand wave modelling studies.

5 CONCLUSIONS

In this work we have shown the potential of high temporal and spatial bathymetric data to be used for the detection of sand wave migration on short timescales. Overall the data reveals a low average migration and no clear trend in direction, but locally high variations are observed. Moreover, bidirectional migration is visible on all sand banks.

The high spatial resolution also reveals the presence of megaripples on practically all stoss slopes of the sand waves, in contrast to the smooth lee slopes. This emphasize the importance of resolving spatially varying roughness elements in morphodynamic sand wave models.

6 ACKNOWLEDGEMENTS

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