The variability of sand wave migration in the North Sea

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ABSTRACT: The morphology and dynamics of marine bedforms are spatially variable. This variability is of interest to both scientists and users of those seas where dynamic bedforms occur. Physical morphodynamic models simulate the formation and behaviour of sand waves. However, to date, empirical time series of bathymetric data that are accurate enough to measure migration rates, in order to test these models, are scarce. This paper presents the variability of sand waves in the North Sea, by analysing bathymetric data both in plan view and cross section, using a cross-correlation and truncated 1D and 2D Fourier analyses. Results show that sand waves may not migrate perpendicular to the crest orientation, but in an oblique direction. Resulting migration rates among sites vary from approximately 0 m a^{-1} to 20 m a^{-1}, with the most dynamic sand waves at coastal sites and more stable sand waves offshore. Smaller scale local variations in migration rates and directions are apparent along sand wave crests. Variations in the migration in time are observed, though are less than variations in space. Linking the dynamic parameters to local conditions will provide insight in the explanation of the variability in the morphology and dynamics of sand waves.

1 INTRODUCTION

Sandy sea beds are commonly characterised by dynamic bedforms of different spatial scales, of which sand waves are defined as rhythmic bedforms with wavelengths between 100-1000 m, wave heights between 0.5 and 18 m and crest orientations approximately perpendicular to the principal tidal flow direction (e.g. Ashley, 1990). Sand waves are generated by residual vertical circulation cells, whereby sediment at the bed is transported towards the crests (Hulscher, 1996; Komarova & Hulscher, 2000), which is the process of sand wave growth. The migration, another dynamic characteristic of sand waves, is caused by a tidally induced residual flow (Németh, 2003; Németh et al., 2002; 2007) and higher tidal constituents (Besio et al., 2003; 2004; 2006).

Recent studies of sand waves in the southern North Sea show that both morphology and migration rates are variable among sites (Knaapen, 2005; Van Dijk & Kleinhans, 2005; Van Dijk et al., in review). Their morphology may vary from elliptical (3D) sand waves on top of shoreface-connected ridges to straight (2D) or sinuous sand waves offshore, from asymmetric to symmetric sand waves, with average wavelengths between 150 and 760 m and heights between 0.5 and 13 m. Migration rates, as observed so far, range between 0 and 20 m a^{-1} between offshore and coastal sites respectively (Van Dijk & Kleinhans, 2005). This variability in dynamics was explained with the relative contribution of current and wave action (Van Dijk & Kleinhans, 2005). Higher migration rates are reported for sand waves in tidal inlets, e.g. 90 m a^{-1} (Buijsman, 2007).

Understanding the variability in morphology and dynamics is important not only to scientists, but also for users and policymakers of the North Sea, for example for selecting suitable locations for wind farms, risk assessments for cables and pipelines, safe navigation, the marine aggregate industry, and for the design of hydrographic monitoring surveys. Most process-based research and literature on sand wave dynamics, to date, is morphodynamic modelling, which is very successful indeed in explaining the role of hydrodynamic and sedimentological factors. However, for the purpose of understanding the variability in sand wave formation, evolution, and migration, we also need observations of different sand waves under various local conditions, not only to validate the model results, but also to test whether model assumptions are justified. Still, recent accounts of sand wave migration in the southern North Sea, using time series of multi-beam echo soundings, which are sufficiently accurate for dynamic investigations, are limited to 1D analyses of small areas or a small number of areas as examples to present their analytical methods (Dorst et al., 2006; Knaapen, 2005; Van Dijk & Kleinhans, 2005; Van Dijk et al., in review), whereas only a good spatial representation of bedforms can provide the understanding of processes of bedform evolution and dynamics. Older accounts are more extensive in terms of number of observed sand waves or covered area and in number of sites (Flemming, 1988; Lanckneus & De Moor, 1991; Terwindt, 1971; Tobias, 1989), but merely focus on the morphology since the determination of dynamic parameters was impossible due to the inaccuracy of the single-beam echo sounding data and manual analyses (e.g. Németh, 2003; Terwindt, 1971). Although most investigations of sand wave dynamics to date are one-dimensional, a few recent studies include a plan view analysis (e.g. Buijsman, 2007; Duffy & Hughes-Clarke, 2005; Lindenbergh et al., 2007; and in a way Knaapen, 2005). However, most of those studies lack the plan view analysis of shape or pattern change and lack a critical test about migration direction, but instead assume a migration direction normal to the crests, as assumed in models. In this paper, our results will show that the direction of maximum migration is not always perpendicular to the sand wave crests, and thus that this assumption is invalid.

In this paper, we aim to present a quantitative morphodynamic analysis of sand waves from digital empirical data both in cross section (1D) and in plan view (2D), and to present the variability of sand wave migration in the southern North Sea. This dataset will be the first comprehensive dataset of empirical variability in 2D migration rates in the North Sea, which will allow for the testing of causal relationships between sand wave characteristics and local and regional conditions, such as the hydrodynamic regime (tidal current and wave), bathymetry, sedimentology and external factors from empirical data. Plan view modelling of sand wave pattern evolution still has to be incorporated in physical morphodynamic models.

2 METHODS

Multi-beam echo soundings (MBES) were acquired using a Kongsberg Simrad EM3000 and 3002 (vertical accuracy 0.15 m) at 300 kHz and a dGPS system for horizontal positioning (horizontal accuracy 1 – 2 m). Single-beam echo soundings (SBES) were made available by the Hydrographic Service of the Royal Dutch Navy, in order to extend time series. Data density of the MBES is on average 3 observations per m^2 whereas the SBES were sailed with a minimal distance between tracks of 50 m and observation distance along the line ~5 – 30 m. Decreased accuracy due to lower density and less accurate positioning systems is acceptable, because time series are prolonged with 10 years and thus displacements are larger. Older manual maps of the Hydrographic Service may be used for the same purpose to extend the period of observation; although the horizontal positioning accuracy of these maps is hundreds of metres, these are still valuable, as they may extend the time series with up to 30 years.

For the morphodynamic investigation of sand waves, the digital echo soundings are firstly interpolated into grids, or surfaces (digital terrain models); three types of interpolation (average, median and Kriging) may be tested for the best performance, which in most cases is Kriging. Secondly, calculating height difference maps of the interpolated grids in GIS will give a good estimate and overview of the expected dynamics, both for pattern changes in plan view and migration rate and direction estimates. A cross correlation is applied, comparing the geomorphological pattern of 2 grids in time and providing a regional displacement as a vector. The regional correlation is justified because the pattern of sand waves is relatively stable so that patterns can be correlated well. With a 2D Fourier spectral analysis of the surface, the average orientation and the dominant (regional average) wavelength of bedforms are determined. Profiles normal to the crests and in the direction of displacement, as derived by the cross correlation analysis, are compiled by resampling the interpolated surfaces. From these profiles, the crest, trough and inflection points are determined in an automated way, using a Fourier approximation that is truncated at certain wavelengths, in order to separate the sand wave signal from the megaripple and large-scale morphology signals (for details of the method, see Van Dijk et al., in review). With the known locations of those points, the morphology (wavelength, wave height and asymmetry) can be quantified and the dynamics (growth, change in asymmetry, horizontal and vertical migration) can be calculated. Finally, and similarly to the 1D Fourier, a truncated 2D Fourier series of the surfaces on which principal directional curvature calculations are applied, allows for the determination of crest and trough line locations, which can be used to detect plan view migration variations along sand wave crests (see Van Dijk et al., in review).

An error estimation for each step in the method of analysis, provides a handle on the accuracy and validity of the outcomes. Herein, the accuracy of interpolated grids is expressed in terms of reproducibility of the data points, rather than the difference between the interpolated grid and point measurements. Determination of the crest and trough points with the Fourier approximation is exact.

Data time series vary from 2 to 11 surveys over periods the longest of which is 1968 to 2007 with time intervals of at least 1 year to shorter time series of 5 surveys over 1.5 years with intervals of a few months.

3 RESULTS: SAND WAVE MIGRATION

3.1 *Migration direction*

The combination of a cross correlation analysis and a 1D Fourier analysis of profiles reveals that migration rates in the cross correlation direction are indeed higher than migration rates normal to the crest direction, for example for the sand waves just offshore Texel, Netherlands (Table 1).

Table 1. The migration of crest points calculated in the directions normal to the crests and in the direction of displacement derived by the cross correlation, for sand waves off the coast of Texel, Netherlands.

Migration	Regional	Averaged	Average rate
	m	M	m a^{-1}
Normal		189	17.6
Xcorr	212	214	19.9

These results show that the maximum migration is significantly larger than the migration normal to the crests, which differs 2.3 m or 13% in this example. This suggests that the assumption that sand waves migrate normal to their crests orientation is not valid.

3.2 *Variability in time*

The analysis of longer-term time series, including manual maps, SBES and MBES data, resulted in profiles of bedforms that revealed varying migration rates between sites but fairly constant net rates per site in time. Figure 1 gives an example of several surveys offshore Rotterdam, Netherlands. These profiles show that the accuracy of bathymetric measurements is higher of the modern data, but that the older data from manual charts still is useful in this series, since it supports the regional difference in sand wave height and prolongs the period for the migration rate estimate with 26 years.

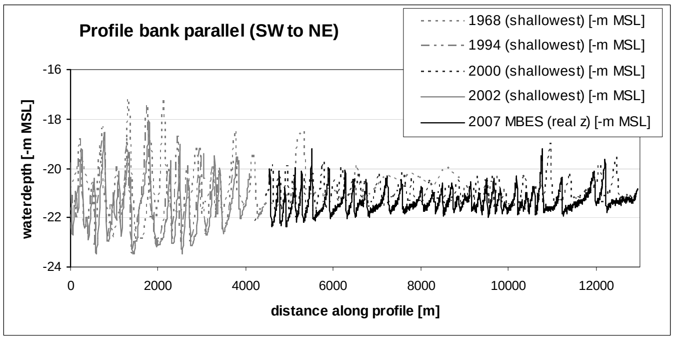

Figure 1. Profiles of surveys from 1968 to 2007 for a site offshore Rotterdam, Netherlands. 'Shallowest' in the legend refers to data processed by the Royal Navy to only keep the shallowest point in cells of 5 * 20 m, and 'real z' refers to real depths in the MBES data of 2007, which was acquired by Port of Rotterdam N.V.

Time series with shorter intervals suggest a seasonal variation in migration rates. Lee slopes of sand waves at a site 50 km offshore of Egmond aan Zee, Netherlands, migrate back and forth, with a net migration rate of 2 m a^{-1}.

3.3 *Regional variability in space*

The longer-term net migration rates at different sites in the North Sea vary from approximately 0 m a^{-1} (stable) at offshore sites to 20 m a^{-1} at coastal sites. Also, migration rates seem to vary among locations that have different underlying large-scale morphology, for example, sand waves on top of tidal ridges or in the adjacent swales. Crest orientation and presumably migration rates, vary on slopes of tidal ridges.

3.4 *Local variability in space*

The 2D Fourier analysis of sand wave evolution shows that migration rates vary along the crests or troughs of sand waves. Sand waves change in shape, for example, crests may become straighter. The highest dynamics appear to occur near the bifurcation points of sand waves (e.g. Fig. 2).

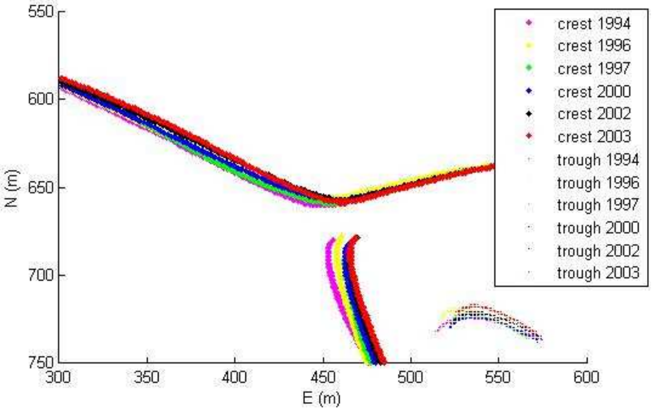

Figure 2. Plan view migration analysis of 1 sand wave offshore Rotterdam, Netherlands, showing a variability in direction and distance of displacement in a bifurcation zone.

4 DISCUSSION

Initial visual comparison to the tidal ellipses in the southern North Sea (Van der Giessen et al., 1990; for a comparison alike see Knaapen, 2005) shows that larger current velocities near the coast correspond to higher migration rates of sand waves. This also corresponds to the findings of Van Dijk & Kleinhans (2005), who find that migration rates are higher in coastal sites than offshore. Van Dijk & Kleinhans explain that, when comparing sediment mobility parameters to merely local tidal current velocities and surface wave heights, that not currents, but the orbital motion propagated to the bed due to surface waves may be the dominant factor in the sediment mobilisation that may explain the spatial variability in sand wave migration. Results also suggest that sand wave orientations and migration rates are affected by the larger scale morphology. Hypotheses that follow from morphodynamic modelling, that the residual current and higher tidal constituents cause bedform migration and back-and-forth displacement respectively (e.g. Besio et al., 2004; Németh et al., 2002), will be tested with these empirical migration rates and local hydrodynamic conditions.

Other factors, such as grain size, will be tested as causal factors of the variability in sand wave migration rates in the North Sea.

Seasonal variability of the dimensions and migration of sand waves, that is merely suggestive from our data sets, but was also found by Buijsman (2007), who investigated an excellent time series of 7 years with intervals of 0.5 hours of MBES and velocity profiles.

5 CONCLUSIONS

The plan view analysis of accurate bathymetric measurements is crucial in the investigation of sand wave migration rates, since it is now revealed that sand waves may not migrate normal to their crest orientation, but in an oblique direction. 1D analyses of profiles and 2D analyses of surfaces allow for detecting the pattern change and spatial variability in migration rates and directions both on a regional scale and on a local scale along sand wave crests. Sand wave migration rates in the southern North Sea range from 0 m a^{-1} offshore to 20 m a^{-1} near the coast, which may be explained by the larger current velocities and wave action at the bed.

These results may lead to the explanation of causal factors in the variability of sand wave migration and encourage modellers to incorporate plan view changes in sand wave morphology into their morphodynamic models.

A future opportunity of these quantitative analyses is the upgrading of the morphological map existing to date (Van Alphen & Damoiseaux, 1989) and initiating the mapping of sand wave migration in the North Sea, which is of interest to both scientists and offshore developers. Another wider implication of this research is the assessment of how benthic ecology is affected by variable morphodynamics in their habitats.

6 ACKNOWLEDGEMENTS

Data were collected in collaboration with the Dutch Ministry of Transport, Public Works and Water Management (RWS), by the Hydrographic Service of the Royal Dutch Navy, and by the Port of Rotterdam N.V.. This research was funded by Delft Cluster, and contributes to the EU-project MESH (Mapping European Seabed Habitats, http://www.searchmesh.net).

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