Sand wave dynamics: Surfing between assumptions and facts

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ABSTRACT: The quality of field-based research is significantly dependent on the accuracy and the conceptional approach of the used methods. This paper will give a brief overview of the state-of-the-art technology by which bedforms on different scales such as sand waves, dunes and ripples can be detected in the field. It will discuss aspects of an integrated approach using different underwater acoustic remote sensing technologies, and demonstrate that acoustic data do not always show the real situation at the seabed. The need for higher quality data increases with the hydrodynamic and morphodynamic complexity and variability of an environment.

1 INTRODUCTION

Numerous bedform studies have been carried out in marine, estuarine and riverine environments focussing on a variety of aspects. To understand morphological and sedimentological features and their internal sedimentary structures, bedforms and related hydrodynamic and sediment transport processes and conditions have been investigated on a number of different temporal and lateral scales (e.g. Allen 1968; Allen & Collins 1974; Flemming 1988, van den Berg 1987; Ernstsen et al. 2005; Parsons et al. 2005). Dedicated research has always approached a combination of observations, measurements, calculations and conceptual, mathematical or physical modelling. A manyfold of empirical and deterministic formulations and two- and three-dimensional transport and morphodynamic models have been developed for tide-dominated shallow seas and coastal areas (e.g. Hulscher 1996; Nemeth et al. 2002, 2007; Soulsby & Damgaard 2005), for rivers (e.g. Jerolmack and Mohrig 2005; Tuijinder et al. 2007), and for paleosystems (e.g. Rubin 1987; Blom and Kleinhans 2007).

Flume experiments have for decades been the most common tool to simulate natural conditions on different dimensions and good correlations between measured and modelled bedload rates have been achieved, e.g. Toyama et al. (2007). Important differences in associated flow and turbulence patterns have been worked out, e.g. by Bennett & Best (1995) and Best & Kostaschuk (2002), while grain size-dependent bedform development and sediment threshold conditions have been studied, e.g. by Bar-

tholdy et al. (2002, 2005), Kleinhans (1995), Ernstsen et al. (2005), Catano-Lopera & Garcia (2006a, 2006b), Friedrich et al. (2007), and Pender et al. (2007). However, the reliability of predictive models and flume-scaled results still needs to be improved and supported by field data. Comparisons of field with model data (e.g. Besio et al. 2006, 2007; van der Mark et al. 2007) illustrate some model limitations, especially with respect to time scales. Models mostly assume longer-term equilibrium, e.g. Németh & Hulscher (2002) and Nemeth et al. 2007, and sand wave saturation heights limited to 20% of the water depth under mostly current-controlled conditions in shallow seas. Yalin (1977) defined the maximum dune height as corresponding to 1/6 of the water depth.

Similar limitations apply to transport calculations. Based on simplified assumptions, existing bedload formulae (e.g. Meyer-Peter & Müller 1948; Yalin 1977; van Rijn 1981, 1984a; Nielsen 1992) often overestimate bedload transport rates (van den Berg 1987; Ernstsen et al. 2005), or are limited to systems without significant suspension loads (Kostaschuk and Best 2005) or to systems dominated by steady flow conditions (Ernstsen et al. 2007).

The most obvious approach to estimate bedload transport, namely to deduce transport rates from temporal changes in bedform height and celerity was initially limited by poor instrument resolution. Thus, long-term migration rates of tens of metres per year were based on bathymetric data collected with single-beam echosounders (e.g. Carling et al. 2000; Bartholdy et al. 2002; Dinehart 2002), side-scan sonar (e.g. Flemming 1978, 1980; Flemming & Bar-

tholomä 2007), and low-frequency multibeam echo-sounders (MBES) (e.g. Diesing et al. 2006). Today, high-resolution MBES bathymetry allows generation of fairly exact 3D digital terrain models (e.g. Dijk & Kleinhans 2005; Duffy & Hughes-Clarke 2005; Ernstsen et al. 2005, 2006b; Knaapen 2005; Knaapen et al. 2005; Paschier & Kleinhans 2005; Parsons et al. 2005; Barnard et al. 2006; Noormets et al. 2006; Albers and Lieberman 2007).

Transport-rate calculations are based on dune geometry data such as height, length, migration rate and particle size (e.g. Flemming 2000; Bartholdy et al. 2002, 2005). High-resolution bathymetry combined with high-accuracy positioning (horizontal and vertical changes at centimetre-scale) now allows snapshots of bedform systems in time and space with either simple 2-dimensional or more complex 3-dimensional geometry. The geometry of fully developed 3D compound dunes can be measured within a single transect. But it becomes more complicated when dune migration periodically changes direction and rates. This effect is well known from many tidal systems with complex hydrodynamic conditions (e.g. Bartholomä et al. 2004; Kostaschuk and Best 2005; Ernstsen et al. 2006b).

Therefore, the quality of field-based data is highly dependent on the accuracy of data collection and the underlying conceptual approach. This paper illuminates some artefacts which still occur in field measurements due to instrumental limitations, but also in the interpretation of acoustic signals due to discrepancies between assumptions and facts regarding geometry, roughness and grain size.

2 POSITION ACCURACY, LATENCY, VIRTUAL BEDFORMS

Although the internal device accuracy given by the system resolution is known, the accuracy of geo-referenced position availability continues to be a problem, especially in areas where real-time kinematic positioning is not available (Brucker et al. 2006; Duffy 2006; Ernstsen et al. 2006a).

Ernstsen et al. (2006a) carried out specific investigations on the precision of high-resolution MBES. The used RESON SeaBat™8125 MBES operates at 455 kHz with an internal vertical range resolution of about 0.006 m. Combined with an AQUARIUS™ 5002 MK/SK (THALES) dual-frequency (L1/L2) long-range kinematic (LRK™) positioning system with an internal resolution of about one centimetre, the horizontal and vertical resolution of the entire MBES system was ±20 and ±2 cm respectively, at a 95% confidence level. With reference to the maximum resolution, Ernstsen et al. (2006a) noted that, in this experiment, the horizontal precision value did not achieve the full potential of the MBES system. Using the same system configuration, internal time

synchronisation problems (latency) related to heave compensation and other external physical properties such as significant changes in sound velocity, can generate artificial bed features similar to natural bedforms of more than ten centimetres in height. This effect increases wherever high-resolution positioning is not available. Due to the patchiness and surface roughness, bedform patterns are artificially degraded, making it more difficult to identify ripple-sized bedforms which are very important for calculations of bedload transport and migration rates over very short time intervals such as single tidal cycles. The inaccurate or wrong definition of the real base of active dunes might be one reason for the overestimation of bedload transport rates. Unfortunately, many authors still refrain from publishing detailed documentation of their system configuration and calibration results. Inter-comparative studies would be a future target.

3 VIRTUAL BEDFORMS BY FREQUENCY AND SIGNAL ABSORPTION - DETECTION OF MUD COVERED BEDFORMS WITH SIDE-SCAN SONAR AND PARAMETRIC ECHO SOUNDER

Due to the physical fact that an increasing frequency results in a higher resolution at a lower range and penetration into the sediment body, a high variability in sediment composition may overprint the real dune geometry. To balance the bedload transport, one important parameter is the height of the dune. In the Weser estuary (German North Sea coast), for example, sandy bedforms incorporate mud layers and/or are temporarily covered with highly mobile fluid mud (Fig. 1).
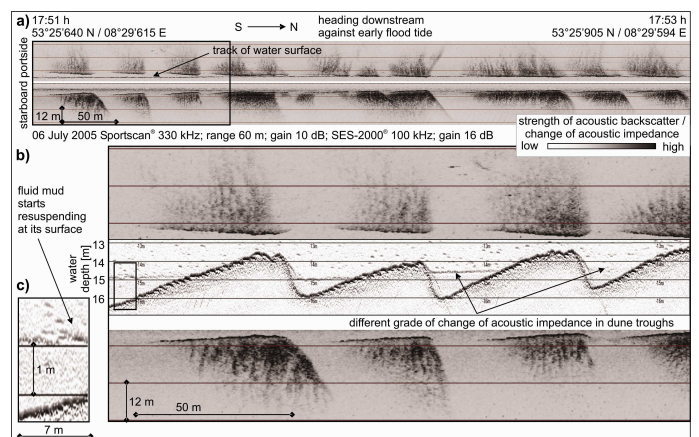

Fig. 1: Longitudinal side-scan-sonar record form the river bed of the Weser estuary (German North Sea coast) (a) with a zoomed section (b), combining side-scan sonar and a parametric echo sounder data (b-centre), showing temporary fluid mud deposits in the dune troughs. (c) zoomed image with 1.2 m thick mud layer over sandy sub-bottom (after Schrottke et al. 2006).

The changing impedance results in an artificial reduction in height and length, an effect observed until the mud is remobilized (Schrottke et al. 2005; Schrottke et al. 2006). The images of the 330 kHz side-scan sonar records close to slack water show hardly any and no reflections in the troughs of the dunes (Fig. 1b, gray-scaled bottom and top image).

This coincides with a change of acoustic impedance in the dune troughs along the longitudinal section of the 100 kHz signal of the parametric echo sounder (Fig. 1b, cross-section in centre). The dunes are close to 50 m in length and 2.5 m in height. It is obvious that nearly one-third of the real dune height is temporarily hidden by the mud. The effect of signal adsorption is always relevant in backscatter related systems such as MBES and side-scan sonar. Amalgamation of compound dune systems, for example, can be temporarily disguised by this effect. With the integrated approach of combining a high-frequency sonar system (MBES, side-scan sonar) and a parametric echo-sounder, the true geometry of bedforms covered by such mobile sediment can be easily recognised.

The opportunity of high-frequency acoustic surface scans makes it also possible to detect mobile bottom layers caused on different acoustic behaviour. For that purpose, the variability of the acoustic impedance of bed and/or suspension loads has to be characterized. Suspended matter has been detected with different types of Doppler technology at various resolution scales using ADCP (Acoustic Doppler Current Profiler) systems in the Fraser river (e.g. Kostaschuk et al. 2004; Kostaschuk and Best 2005), in the Dutch Wadden Sea (Elias et al. 2006), in the Danish Wadden Sea (Ernstsen et al. 2006b), and in the Ems and Weser estuaries along the German North Sea coast (Becker et al. 2007). The in-situ suspended sediment concentration within the entire water column was calculated by calibrating the ADCP backscatter signal with measurements of particle concentrations in water samples. Simultaneous deployment of a high-resolution parametric echo sounder, high-frequency MBES and ADCP, optical backscatter (OBS) together with high-precision positioning system now enable the registration of bedform mobility and bedload transport rates even in estuaries characterized by high suspension loads along the German North Sea coast (Schrottke et al. 2007).

4   WATER DEPTH, ROUGHNESS, GRAIN SIZE DEPENDED DUNE SIZES

As mentioned earlier, dune height is commonly considered to scale with water depth (e.g. Yalin 1977; Van Rijn 1984b). This concept is mainly based on flume studies and observations in very shallow water, e.g. rivers. In such situations, the water depth acts as an upper boundary to the growth of dunes. For example, this dependency has been observed in the river Rhine by Carling et al. (2000). Along the Dutch coast, van Dijk & Kleinhans (2005) found different migration rates in asymmetric and flattened 3-D compound coastal sand waves and 2-D sharp-crested compound offshore sand waves having nearly the same grain size composition. They distinguished two areas, one in a deeper offshore sector with no boundary limitations, another one in the shallower coastal sector where higher orbital wave velocities impact the bedform heights.

In contrast to this classic concept, Flemming (2000) documented a positive relationship between maximum dune dimensions and grain size, assuming sediment abundance. The maximum possible dune height is reached when the flow acceleration above the dune crests reaches a grain size–dependent critical suspension velocity. Field studies of tidal channels in the Danish Wadden Sea confirm this dependency. Bartholdy et al. (2005) showed that, in the Grådyb tidal channel under near-constant dominant flow conditions, superimposed simple depth-independent dunes vary in size according to the grain-size at a constant water depth which was one order of magnitude larger than the height of the dunes. These studies demonstrate that grain size requires much more attention in field studies, and larger areas of individual bedforms should be covered by grain-size data derived from grab or boxcore samples. In complex compound 3D-dunes, particle-size distributions were found to show a high lateral heterogeneity (Ernstsen et al. 2005).

Today, ground-truth grain-size data should only be used for calibrating fully covered acoustic surface roughness detection. Combined with high-resolution bathymetry, different surficial sediment patterns can be detected by wave shape analysis of the acoustic signal generated by single-beam echo-sounders (e.g. Collins et. al. 1996; Hamilton et al. 1999; Ellingsen et al. 2002; Walree et al. 2005), backscatter analysis from side-scan sonar records (e.g. Goff et al. 2000; Collier & Brown 2005), or MBESs (e.g. Hughes-Clarke et al. 1996). An extensive overview of the different approaches of acoustic classification is given by Hamilton (2005). According to the resolution of the depth information, acoustic return signals contain information on both hardness and roughness which at least reflect the most important characteristics of the sediment surface. Calibrated by bottom samples and visual observation, acoustic grain-size information was classified in the range from mud to gravel by e.g. Simons et al. (2004). Based on multivariate statistical analysis of individual echo features, Walree et al. (2005) discriminated grain sizes between 0 phi (1 mm) and 6 phi (0.016 mm) extracted from different frequencies. Dune migration and reestablishment combined with spatial acoustic sediment classification before and after dredging ac-

tivities has been studied by Wienberg and Bartholomä (2005). In undisturbed areas, increasing dune size correlated with larger particles, the dune morphology of the sonar images generally matching with the grain-size distribution. However, along the dredged navigation channel, small dunes consisted of a complex pattern of highly mixed sediment showing no small-scale grain-size gradients in relation to varying dune geometry.

The complex morphology in the compound dune system of the Grådyb channel (Fig. 2) (Bartholdy et al. 2005; Ernstsen et al. 2005, 2006b) is also closely linked to the distribution pattern of the surface sediments (Fig. 3).
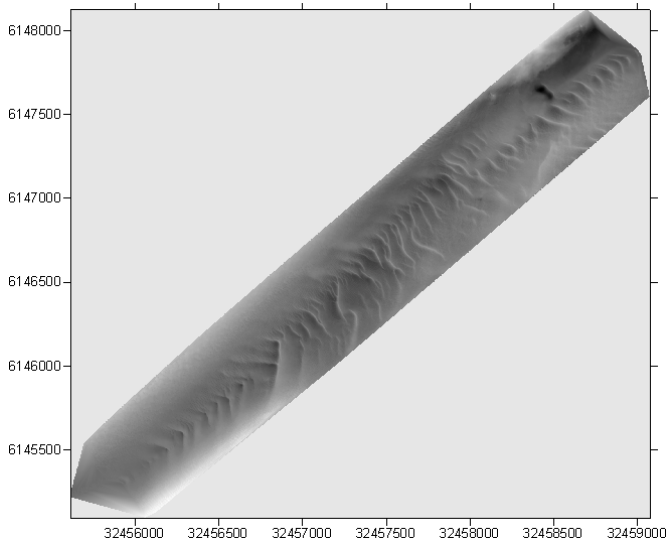

Fig 2: MBES record of the Grådyb channel with a grid size of 2x2 m in 2005

On the basis of single-beam acoustic seabed classification surveys in 2005, five main seabed types have been identified in the channel, ranging from fine sand to medium gravel.
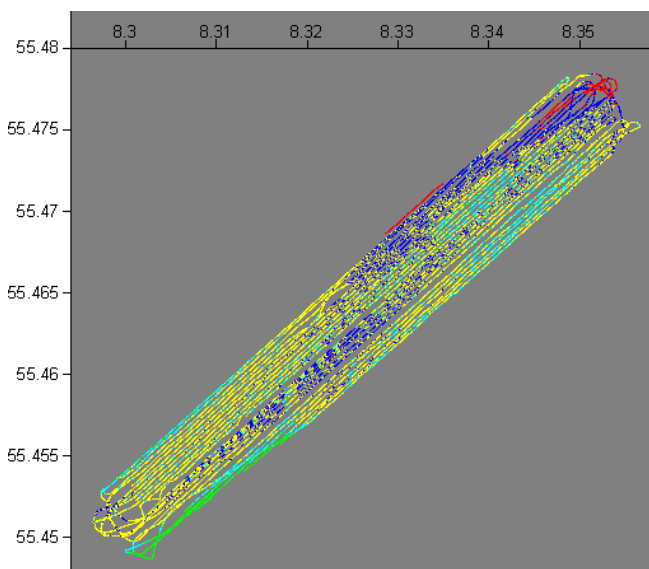

Fig. 3: Distribution of the surface sediments in the Grådyb tidal channel (Danish Wadden Sea) based on acoustic seabed classification with 5 classes ranging from fine sand to gravel (2005) – The regular change in the channel centre illustrates the complexity of the dune sediments here.

Corresponding to the dune pattern, the centre section of the channel is characterized by a regular pattern of changing seabed classes which gradually switches from one channel side (NE) to the other (SW) (Fig. 3). The data reflect the general hydrodynamic situation of the meandering main flow which follows the morphology. The resolution of this type of data is strongly dependent on the systems footprint size with varies with the hardware resolution of the acoustic system and water depth. Quite obviously, future system developments must focus on the swath technology, which needs more effort in acoustic corrections but, at the same time, enabling smaller footprint sizes and larger coverage.

5 BOUNDARY LAYER (NEAR BED) FLOW STRUCTURE AND SEDIMENT TRANSPORT

The characteristic patterns of bedform dimensions and their lateral distribution and mobility strictly interact with the variability of currents and waves. For greater water depths, estimations and calculations are mostly based on an average particle density, mean particle size and mean flow velocity, parameterizations which are evidently sufficient for large-scale and long-term modelling approaches, as for example discussed in van Dijk and Kleinhans (2005). In shallow water, by contrast, waves may cause high orbital velocities at the bed, thereby generating a wave bottom boundary layer with a thickness in the order of several centimetres. Since wave-generated bottom boundary layers are much thinner than current-generated ones, they cause higher bed shear stresses for the same velocity values (Fredsøe and Deigaard 1992; Soulsby 1997), and are thus much more effective in mobilizing sediment. But these models and calculations assume exclusive physically controlled systems. Biological activity is, with rare exceptions (e. g. Borjse et al. 2007) not considered. Such activity, however, impacts the rates and type of near-bed transport, and even influences the boundary layer thickness. With high-resolution velocimeters, 3D velocities can be measured at millimetre resolution close to the bed which can then be easily converted into shear-stress values. To measure such velocities in the field, Doppler technology in the form of ADCPs (e.g. Kostaschuk & Best 2005; Parsons et al. 2005), Pulse Coherent/Acoustic Doppler Profiler (PC/ADP) (Lacy & Sherwood 2004), Acoustic Doppler Velocity-metre (ADV) (Williams et al. 2003), Acoustic Backscatter System (ABS) (Betteridge 2001 et al.; Williams et al. 2003) has

been extensively used in recent years. Williams et al. (2003) confirmed that similar results in current speed and shear velocity were obtained by different instruments for vertical profiles in water depths up to 0.5 m. Comparing flume and in situ measurements of near-bed current velocities obtained by an ADV and high-resolution bathymetry by an ABS, Karle (2008) recorded significantly different threshold values for the remobilisation of sediment having the same grain-size composition. Critical hydraulic conditions for sediment remobilisation were determined on the basis of turbulent kinetic energy (TKE), Reynolds stress and high-resolution echo-sounder profiles combined with side-scan sonar data. In all cases, the sediment surface remained stable up to flow velocities which were 50 % higher than the critical erosion velocities determined in the flume experiments. This was attributed to biological stabilisation effects in nature. However, it was also demonstrated that bio-stabilisation was only effective at low to moderate energy levels under current-dominated conditions. Increasing wave activity will result in higher turbulent kinetic energy values and hence further reduce the effectiveness of bio-stabilisation. Case studies from Dutch (Williams et al. 1999, 2003) and British (Pope et al. 2006) tidal systems correspond in the dimension of shear stress values with some variation in bed roughness.

6   DUNE MIGRATION RATES MEASURED BY DUNE TRACING

Divergences between field and model results of dune migration and bedload transport may also be affected by different procedures of data analysis. Defining migration of dunes requires several measurements of identical markers in space and time. Most of the studies working with transect lines use hand-picked longitudinal profiles (e.g. Bartholomä et al. 2004; Ernstsen et al. 2005, 2006b, 2007; Besio et al. 2007). For simple 2D dune systems, predictive models are reliable (e.g. Nemeth et al. 2002; Besio et al. 2004). Knaapen (2005) developed a robust algorithm to estimate long-term sand wave migration from bathymetric echo-sounding data based on sand wave shape. He personally did not recommend this tool for seasonally affected short-term mobility. Stockmann (2005) adapted additional algorithms to the image processing software MorphDyn© which allows the creation of DTM-volume differences. But this was used on very simple geometric features at dredging localities.

The spatial cross-correlation application of Duffy & Hughes-Clarke (2005) is a method which quantifies and locates regions of maximum similarity between two spatial variables. For this purpose, they used MBES data on the basis of which they were able to determine migration rates down to a bedform

size of nearly 30 cm. The limitation of this approach is the repletion rate of surveys relative to the migration rate where the fastest bedforms may have moved a maximum of 50 % of their spacing interval during a single survey.

Spectral wave analysis is a quite common approach in physics. Winter & Ernstsen (2007) decompose successive bathymetrical dune profiles by means of Fourier analysis. The change in size then can be determined by differences of amplitudes, whereas migration could be calculated from the difference in phase. In a first model step they simulate a two month period. While the general morphological units of the dunes could be reconstructed, the reconstruction of the asymmetric orientation in the real bathymetry failed.

Resolving complex 3D-dune migration rates under multi-directional current and wave conditions with automatic tools is currently still poorly developed and will require further technological efforts in the future.

7   ACKNOWLEDGEMENTS

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