Bedforms and Bedform Migration: A Data Review

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Abstract

Published data on migration of bedforms on the sea floor are reviewed and discussed. Although certainly not all data were available, conclusions can be drawn. Guidelines for future more reliable determinations of bedform migration rate can be deduced.

The reviewed data have variable accuracy. Analyses show that (i) migration rate decreases with increasing bedform height, (ii) sand dunes higher than 1 m generally do not move much, (iii) megaripples of up to 50 cm height migrate with up to 50 cm/day, but also much faster under yet unknown circumstances.

Continuous long-term observations exhibit significant local and temporal variability of the speed of single megaripples, leading to the conclusion that isolated measurements of single bedforms do not give a representative information for an area.

Introduction

For a long time bedforms have been observed on the sea floor. Since a few decades their mobility is investigated. This paper concentrates on bedforms oriented perpendicular to currents. They can be widespread or localised in channels, rivers, their estuaries, but also in the open sea. For many applications they have high importance. The smallest bedforms, ripples are not considered here.

Megaripples (here: $h \leq 1.5$ m, $L \leq 30$ m) are often also called sand dunes or sand waves. The term "sand wave" is not used here because it implies a symmetric (wave-like sinusoidal) shape which is not found for migrating bedforms. The heterogeneity in nomenclature can lead to severe confusion since the next higher class of bedforms which is larger than 1.5-2 m and relatively stable in their positions, is also associated with these names. In this paper the classification "ripple / megaripple / sand dune" is used (Wever and Stender, 2000). Wever and Voß (2003) discussed the dilemma of nomenclature and partly contradicting observations in detail. Finally, larger bedforms that are immobile are not discussed here. Depending on location the characteristic heights and cross-section lengths may vary and the hierarchy has to be considered, too.

Megaripples move on the sea floor with a dominating direction. Sediment transport by migrating bedforms nearly exclusively occurs via megaripples (Stender, 1996). Therefore, the term "migrating bedform" is restricted in this paper to them.

Methods

Various methods for investing migrating bedforms have been reported. A direct approach to the problem is determining the displacement of bedforms on the sea floor at different times. This tactic was severely impaired until the mid-90s by uncertainties of position errors. Many data sets included in this review are based on this method.

The precise determination and re-localisation of positions required for a reliable resolution of migration rate has not been available for a long time. In the North Sea, e.g., errors of 50-80 m were normal with DECCA navigation, which excludes a trustworthy estimate of bedform migration rate. The introduction of differential GPS provided a position accuracy, which allowed to monitor the slow changes of the bedform position.

The identification of single bedforms in repeated (often echo sounder) measurements is a key problem: a too long time between successive campaigns will not guarantee that the same bedform was observed. If bedforms are confused, the migration speed error can easily be 100%. This difficulty is aggravated by the irregular migration of bedforms, their sudden stopping, the amalgamation of neighbouring bedforms. The latter factor causes changes of form (height, length) and makes an identification difficult or even impossible.

The identification of bedforms is even more complicated by changes in their height (and other characteristics) as they move upwards on the flanks of sand dunes. Terwindt (1971), for example, reports that megaripple heights increase from 0.3-0.7 m in the sand dune troughs to 1-2 m near the sand dune crests. Stender (1996) reports similar observations (in troughs: 0.3-0.5 m, near crests: 0.7-1.5 m) whereas Langhorne (1977) reports a weak opposite correlation. Other reported influences on bedform height are seasonably variable fresh water masses in rivers.

Another prominent error source arises from the re-orientation of the crests of even up to several meter high sand dunes under the tidal influence (Wever and Voß, 2003). This occurs without any movement of the bedform base itself. It changes the bedform shape and the crest migration may pretend a bedform movement. *It is thus advised to make and compare only measurements of the same time of the tidal phase*. Otherwise only the tidally caused re-orientation is determined instead of actual bedform movement. In the evaluated papers only Langhorne mentioned that this aspect has been taken into consideration!

Some researchers avoided the position problem using fixed markers such as blocks of concrete, stakes in defined distance, or registration mines on the sea floor (Jones et al., 1965; Salsman et al., 1966; Langhorne, 1982; Stender in the 1970s, see Wever and Stender, 2000). While the first two approaches required regular diver observations, Stenders registration mines were able to determine their degree of burial at regular intervals over long periods. The ability to operate this system during sea states that do not permit diving is especially advantageous. The experiments were made at more that 10 m water depth in the sub-tidal.

Another direct method to determine the migration rate of megaripples has been used especially in the Netherlands and western Great Britain: Rivers and harbour entrances that fall dry during ebb slack water were furnished with stakes or similar markers. Accurate measurements were taken during ebb. These measurements from the inter-tidal can give interesting clues but their relevance to sub-tidal bedform migration is limited. The reason is that the streaming water comes ever closer to the surface of the sandy bedforms and finally break through the water surface. Then, completely different physical processes of sediment transport control the result than in deeper water. Much higher migration rates and lower bedform heights are to be expected. However, because of the better overview such data are also mentioned in this report.

Sediment transport prediction

Approaches exist to determine bedform migration rate directly from current speed. However, published formulae often hold only for single experiments. In rivers formulae were derived which show a dependence on current speed to the 3rd to 5th order, but occasionally even higher orders were found.

A different approach is based on the erosion of sand grains and on estimates of transported volume. This method suffers from often contradicting observations. E.g., Amos and King (1984) demonstrated by field measurements that coarser sand grains required lower velocities of tidal current to generate "sand waves". A coarsening of sediment results in enhanced bedform generation. Contrasting conclusions were reached by van Niekerk (1993) from laboratory measurements: grain size had no significant impact on the critical current speed at which sediment transport starts, although the data for two investigated grain sizes could be interpreted to support Amos' and Kings (1984) conclusion. The influence of two fixed single grain sizes in the two experiments of van Niekerk (1993) in contrast to real sediment grain size distributions of Amos' and Kings experiment is left open.

Dalrymple and Rhodes (1995) found a minimum current speed of 0.5 m/s for the generation of megaripples, though mentioning that this value may increase with water depth and coarser sediment.

Among the variety of parameters that can be measured, sediment supply is usually inaccessible. All calculations have to take for granted a surplus of available sediment which allows the optimum equilibrium size of bedforms to develop depending on grain size, water depth, current speed etc.. This condition, however, may often not be fulfilled, and the comparability of different sites may be restricted. Anthony and Leth (2002) explicitly mention this problem in their report on measurements in the North Sea. They assume that the equilibrium size of bedforms could not be reached due to a shortage of sediment. The promptness of equilibrium development was demonstrated by Nasner (1983) in the river Elbe: only one week after the crests of megaripples were dredged off they had restored to original dimensions ($h \approx 1.2$ m, $L \approx 25$ m). The removal of bedform tops is useless unless the sediment supply is restricted. For a more extended discussion of these aspects see Wever and Voß (2003).

Generally, it has to be considered that migrating bedforms in an area do not all migrate with the same speed (see lime-lapse movie of Wever and Voß, 2003). They or sections of them can stop, they can be overrun by another bedform or two bedforms can merge.

In contrast to analytical approaches to bedform migration rates, the direct measurement of migration offers advantages. The remaining sections of this report refer to such observations.

Literature data

To better understand bedform migration speed besides own data a literature review was made. It was striking how few papers and reports dealt with this topic. Partly the original articles were not available, then secondary sources were used and the original and referring papers are quoted. Many papers and reports suffer from incomplete information about experimental and environmental conditions. In some cases no precise location was given. For details see Wever (2003).

Only data sets giving bedform height and speed were used for the present analysis (Table 1, an extract of a much larger table, see Wever, 2003). This type of data representation was used because bedform height is the only property that has been regularly reported and can be determined with sufficient accuracy. Due to limited comparability inter- and sub-tidal domains were separated. Table 1 also lists the methods, duration of experiment, and authors. Error estimates are available only exceptionally.

For the most relevant information, migration rate of bedforms, data were extremely heterogeneous. Sometimes it was given for the whole measurement period (up to years), sometimes as hourly rate, sometimes for tidal phases. For comparison all data have been transformed to "cm/day". This should be the most valuable information for short-term prediction requirements. Original data, acquired only for one tide or one hour may lead to too high migrations rates.

If only the average migration rate was given, this was adopted for the value in the speed column. For papers which mentioned a range of migration speed, the maximum was taken. In case of bedform height ranges the lowest value was taken because normally the smallest bedforms are the fastest. Bedform height and migration speed of Table 1 are displayed in Figure 1 (bedforms up to 2 m height and speed up to 2 m/day). Figure 2 displays only the sub-tidal data of this compilation.

Discussion

All figures exhibit the inverse correlation of bedform height and migration speed. Migration speeds exceeding 0.1 m per day are questionable in most cases for bedforms with heights of more than 1 m. It is more likely that position uncertainties during repeated measurements play a role, an argument that arises from the age of the experiments.

Another major contribution to exaggerated speeds may come from the repetition of measurements during different phases of the tidal cycle. In such a case not the migration speed of the complete bedform was determined but probably only the re-orientation of the crest or its addition to real bedform movement. Even with high-precision position determination large apparent migration speeds may be detected. Langhorne (1982) included a "phase-factor" by determining the height of mobilised sediment. He seems to have partly observed with his high-precision measurements the "swinging" of sand dune crests instead of the migration of the complete bedform.

In Figure 1 a concentration of inter-tidal milieu bedforms below 25 cm height can be observed. Since the analogy with sub-tidal processes is limited, they have not been included in figure 2. There are only few reliable data sets left related to bedform migration. Fast megaripples that were investigated with fixed markers on the sea floor and which are free of position errors (marked in the Figures with horizontal bars) are not higher than 50 cm.

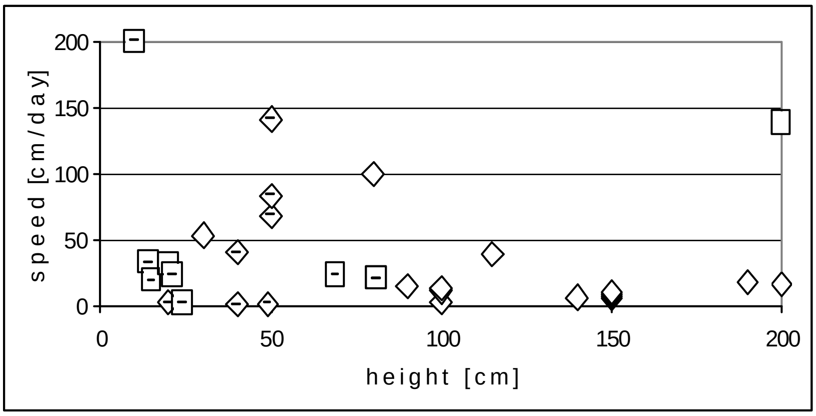

Figure 1: Plot of reported sub- and inter-tidal migration speeds [≤2 m/day] of bedforms (table 1) as function of their height [up to 2 m]. Squares mark the inter-tidal data domain, diamonds indicate sub-tidal data. Horizontal bars mark data obtained via direct measurement (autonomous systems or markers on the sea floor) free of position errors.

Some higher migrating bedforms are relatively fast with ca 25 cm/day, but migration rates may be influenced by position inaccuracies during the experiments or by special and unusual conditions. Volume estimates for the transported material for such fast and high bedforms lead to unrealistic quantities of transported sand. Therefore, these values are not considered reliable.

The data of Figure 2 show five data points with velocities above 50 cm/day and two more with ca 40 cm/day:

a) The high quality values (horizontal mark) were obtained with burial mines and are reliable.

b) For the data point of an 80 cm bedform with migration speed of 100 cm/day (80/100) no information is available about method or age. Most probably the data are repeated echosounder measurements before 1995. Their value for this investigation might therefore be regarded as questionable.

c) The other two data points seem to be realistic, the one with 30 cm height and a speed of 53.2 cm/day (Dalrymple and Rhodes, 1995 cite only 17.2 cm/day) as well as the one of 1.15 m height and a speed of 39 cm/day. The latter one was determined in the river Elbe under high current speed conditions. However, this special situation may not be representative for migrating bedforms that are observed with weaker tidal or steady currents.

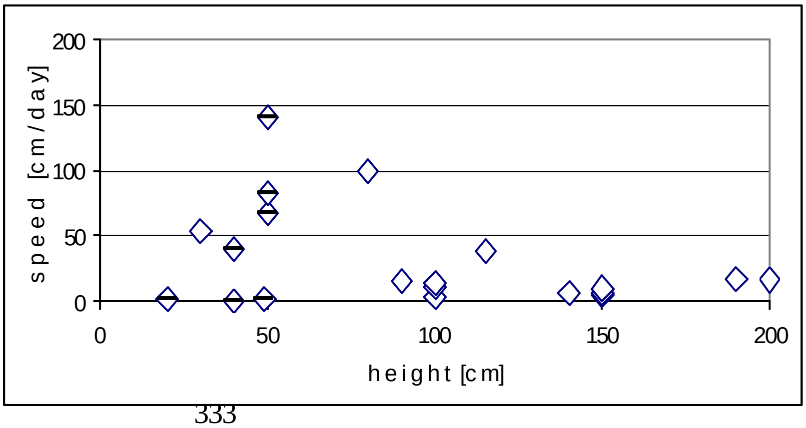

Figure 2: Plot of all reported sub-tidal migration speeds [up to 2 m/ day] of bedforms as function of height [up to 2 m]. Horizontal bars mark data which were obtained via direct measurement (autonomous

systems or markers on the sea floor) free of position errors.

The four fastest megaripples, the speed of which was determined with high accuracy, were found in the Jade or Elbe river estuary (numbers 46-49 of table 1). Here, very strong currents are observed. The migration speeds can be considered to be at the upper limit. Unless a further proof with sufficient high accuracy measurements becomes available migrating bedforms with more than 1 m height should not be expected to travel faster than 10 cm/day. Bedforms reaching up to 50 cm height should generally not move faster than by 50 cm/day. Only under special circumstances faster bedforms must be expected (Wever and Stender, 2000). Mechanisms and controlling environmental conditions (e.g., spring tides) need to be investigated in the future.

The use of migration speed in a certain area requires extreme caution. Measurements of FWG in the Jade area (southern North Sea) show that each measurement reflects only the condition at that site. It may not be representative for a larger area or for longer periods. Measurements with five recording mines in immediate neighbourhood in the Jade did not show any similarities. Especially interesting is the nearly complete uncovering of one mine within half a tide. This indicates the occurrence of a strong environmental situation which, however, is not reflected in any of the other recordings. Of equal interest is the nearly constant burial of another third mine during the displayed period. The recording over several weeks shows obvious differences in migration rate of the bedforms that passed single mines after each other (Wever and Stender, 2000). The variability was also demonstrated with the data of a rotary scanning sonar which were obtained during subsequent slack water phases (Wever and Voß, 2003).

Conclusions

(1) In the open literature most data related to megaripple migration (migrating bedforms) date back to the pre-1995 period (before differential GPS became a standard). Therefore they are considered less reliable due to position uncertainty. An exception are measurements with markers on the sea floor.

(2) Repeated measurements carried out at different tidal phases are a potential source of major data interpretation errors.

(3) The few available reliable data indicate that bedforms of 1 m height or more normally do not migrate faster than 10 cm/day. Experiments have to last long enough to reduce the impact of statistical errors and measurement uncertainties.

(4) Only under special circumstances bedforms with heights of up to 50 cm (megaripples) migrate faster than 50 cm/day.

(5) Migration rates are highly variable with position. Single measurements are not necessarily representative for a larger area and may have limited significance.

(6) The establishment of a reliable prediction of bedform migration requires many more measurements. They must be planned with optimum navigation (very small position errors). In addition, they should always be complemented by current measurements, and where relevant, also include the observation of wave characteristics.

(7) The reason for temporal and spatial variability of bedform migration must be investigated. Standard deviations of predicted values must be predicted as well.

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Table 1

Brief overview of evaluated data. The numbers of the last row identify the data sets in a more extended table (Wever, 2003). Sub-tidal and inter-tidal domains are separated in two columns. Abbreviations of methods: BRM: burial registration mine, BS: bathymetric survey, CM: current meter, Di: diver observation, DiM: direct measurements (inter-tidal zone), E: echosounder, MB: marker buoys, PPLS: pipeline survey, rep. Surv.: repeated measurements, Se: seismic survey, Sta: stakes on the sea floor, W: wave measurements.

Height [cm]	**Subtidal [cm/day]**	**Intertidal [cm/day]**	**Method**	**Period**	**Reference**	**Nr.**
580	10.1		E, Di+MB	2 months	Jones et al. (1965)	1
49	1.34		Di+Sta	849 Days	Salsman et al. (1966)	4
150	6.8		SSS, E	14 Months	Langhorne (1973)	12
30	53.2		CM, E	47 Days	Bokuniewicz et al. (1977)	22
300	0.65		Di+Sta, E	1 Year	Shepard/Hails (1984)	33
40	0.81		Di+Sta, E	1 Year	Shepard/Hails (1984)	34
20	2.25		Di+Sta, E	1 Year	Shepard/Hails (1984)	35
400	9.04		SSS, BS	7.5 Months	Aliotta/Perillo (1987)	36
150	9.04		SSS, BS	7.5 Months	Aliotta/Perillo (1987)	37
300	9.04		SSS, BS	7.5 Months	Aliotta/Perillo (1987)	38
400	7.62		SSS, Se	7 Months	Fenster et al. (1990)	40
300	9.3		E	86 Days	Houthuys et al. (1994)	42
50	68		BRM	6 Weeks	Wever/Stender (2000)	46
50	83		BRM	6 Weeks	Wever/Stender (2000)	47
50	141		BRM	6 Weeks	Wever/Stender (2000)	48
40	40		BRM	6 Weeks	Wever/Stender (2000)	49
390	0.75		CM, E, SSS	6 Months	Harris (1989)	50
350	25		SSS,E,Di+Sta	7 Months	Langhorne (1982)	51
1200	7.75		E	375 Days	Burton (1977)	52
1200	4.77		E	256 Days	Burton (1977)	53
1200	4.68		E	368 Days	Burton (1977)	54
90	15		SSS, E	175 Days	van den Berg (1987)	58
14		32.64	Sta	5 Weeks	Terwindt/Brouwer (1986)	60
20		403.2	Sta	5 Weeks	Terwindt/Brouwer (1986)	61
100	13.33		E	5 Months	Vollmers/Wolf (1969)	62
290	13.33		E	5 Months	Vollmers/Wolf (1969)	63
200	16.4		SSS, E	7 Years	Pasenau/Ulrich (1974)	64
81		20.31	E,DiM	1 Week-3 Months	Dalrymple (1984)	67
81		20.31	E,DiM	1 Week -3 Months	Dalrymple (1984)	68
24		1.92	DiM	13 Days	Larcombe/Jago (1996)	70
350	15		E	9 Months	Nasner (1974)	74
115	39		E	9 Months	Nasner (1974)	76
320	0.68		PPLS		Bos et al. (1996)- see Maren (1998)	77
260	1.48		PPLS		Bos et al. (1996)- see Maren (1998)	78
500	1.1		E		Carels/Bruinsma (1983)- see Maren (1998)	79
500	5.5		E	6 Years	Jansen (1981)- see v. Maren (1998)	80
360	23.3		SSS, E	10 Months	Lackneus/de Moor (1991)- see v. Maren (1998)	81
150	5		BS, E	5 Years	Lackneus/de Moor (1995)- see v. Maren (1998)	82
190	17.3		E	17 Months	Ludwick (1972)	83
140	6.1		E	17 Months	Ludwick (1972)	84
280	0.68		CM,W,E		Tobias (1983)- see v. Maren (1998)	86

300	0.27		CM,W,E		Tobias (1983)- see v. Maren (1998)	87
370	0.55		CM,W,E		Tobias (1983)- see v. Maren (1998)	88
300	4.1		E	6 Years	van Kleef (1980)- see v. Maren (1998)	89
100	2.74		E	5 Years	Wright (1992)- see v. Maren (1998)	90
15		18.92	CM, Sta, DiM	3 Months	Boothroyd/Hubbard (1996)	92
21		23.04	tracer, DiM	4 Years in summer, Migration: 2 Days	Klein (1970)	95
69		23.04	tracer, DiM	4 Years in summer, Migration: 2 Days	Klein (1970)	96
10		200	CM,DiM	2 Months	Larcombe/Ridd (1995)	100
200		138.5	Sta,DiM	13 Days	Langhorne/Read (1986)	101
20		31.5	DiM?, CM	13 Days	Hughes/Weir (2001)	105
100	10.8		Di, rep.surv., S	37 Days	Gonzales/Eberli (1997)	106
80	100		Di?, E?, rep surv.	6 Days	Soulsby (1997)	107
150	10		E, SSS, DiM		Chakhotin (1977)	108
200	1000		BS, CM	12 Hours	Idier et al.(2002)	109
1000	3.56		BS, CM	2 Years	Idier et al.(2002)	110