Strategies for and results from the investigation of migrating bedforms in the German Bight

Thomas F. WEVER[1], Ingo H. STENDER[2]

[1]Forschungsanstalt der Bundeswehr für Wasserschall und Geophysik (FWG),
Klausdorfer Weg 2-24, 24148 Kiel, Germany.
Fax: (49)431-607-4150
Email: wever@fwg-kiel.de
[2]Retired from FWG

Abstract
The sandy river bed of Elbe River and sea floor of its estuary as well as the Jade estuary sea floor show pronounced migrating bedforms. Experiments to investigate the shape and behaviour of these bedforms included the deployment of sensors for the long-term monitoring of sand height variations during the passage of megaripples, a scanning sonar tower for the determination of bedform length, and a side scan sonar system. Most of the analyses reported here are based on the results of the sand height sensors.
In the Elbe river sand height sensors monitored the passage of megaripples of about 50 cm height within 11 days. Assuming a minimum ripple index of 10 results in a minimum bedform length of 5 m. The resulting migration speed is 45 cm/day. This migration speed represents a minimum value. Any increase of bedform length (and ripple index) results in an increase of migration speed. Data from the Jade estuary prove a minimum migration speed of 94 cm/day.
A long-term deployment of instruments in the Jade river revealed a cyclic pattern of sand height that superimposed on the general continuous increase respective decrease of burial during passage of bedforms. The cyclic pattern correlates with the tidal cycle. It is believed that this characteristic pattern reflects the re-organisation of the bedform crest in response to the tidal currents. The re-organisation of bedform crests is also detected in the variable acoustic response recorded with the scanning sonar tower.

Introduction
Bedforms of variable dimensions (length, height) are known to exist on the sandy floors of German rivers flowing into the North Sea and at the sea floor of the associated estuaries (Fig. 1). Depth sounding surveys with echo sounder allowed the detailed mapping of bedforms (Ulrich, 1973).
Our measurements prove that the observed bedforms migrate much faster than predicted by the scarce published data. An explanation for this difference is the extremely heterogeneous nomenclature used to describe migrating bedforms. In this paper the terms used are defined in Tab. 1. The scaling and definitions may not apply in other areas. The term sand dunes was chosen instead of sand waves because the cross section of the bedform resembles sand dunes known from deserts rather than sinusoidal waves known from the water surface.

Bedform Name	Bedform Length [m]	Bedform Height [m]	Ripple Index
Ripple	< 0.6	< 0,12	5-30
Megaripple	< 20	0.5-1.5	< 20
Sand Dunes	> 20	> 1,5	> 20

Table 1: Bedform types used in this paper. The ripple index R is defined as the ratio of bedform length (L) to bedform height (H). Bedform length and height of ripples are a function of grain size d (L = 1.000 d, e.g., Yalin, 1977), for larger bedforms water depth is the limiting factor.

Published data on migration speed of sand dunes vary considerably in the range of 0-10 cm/day. A 100 m long sand dune needs 1,000 days ($\approx 2\,{}^{3}/_{4}$ years) to migrate over the distance of one bedform length with the fastest reported speed of 10 cm/day (Jones et al., 1965). Reliable data on the migration speed of megaripples are not known. The major problem is that megaripples are both highly mobile and variable in shape. Without permanent monitoring it is not possible to resolve the temporal and spatial evolution of single megaripples. The measurements presented here allow to determine a minimum migration speed of megaripples of about 45 cm/day in the Elbe river and of 94 cm/day in the Jade river during strong current events. The latter value was recorded most probably under special weather/tidal conditions (extremely high current speed, but no storm).

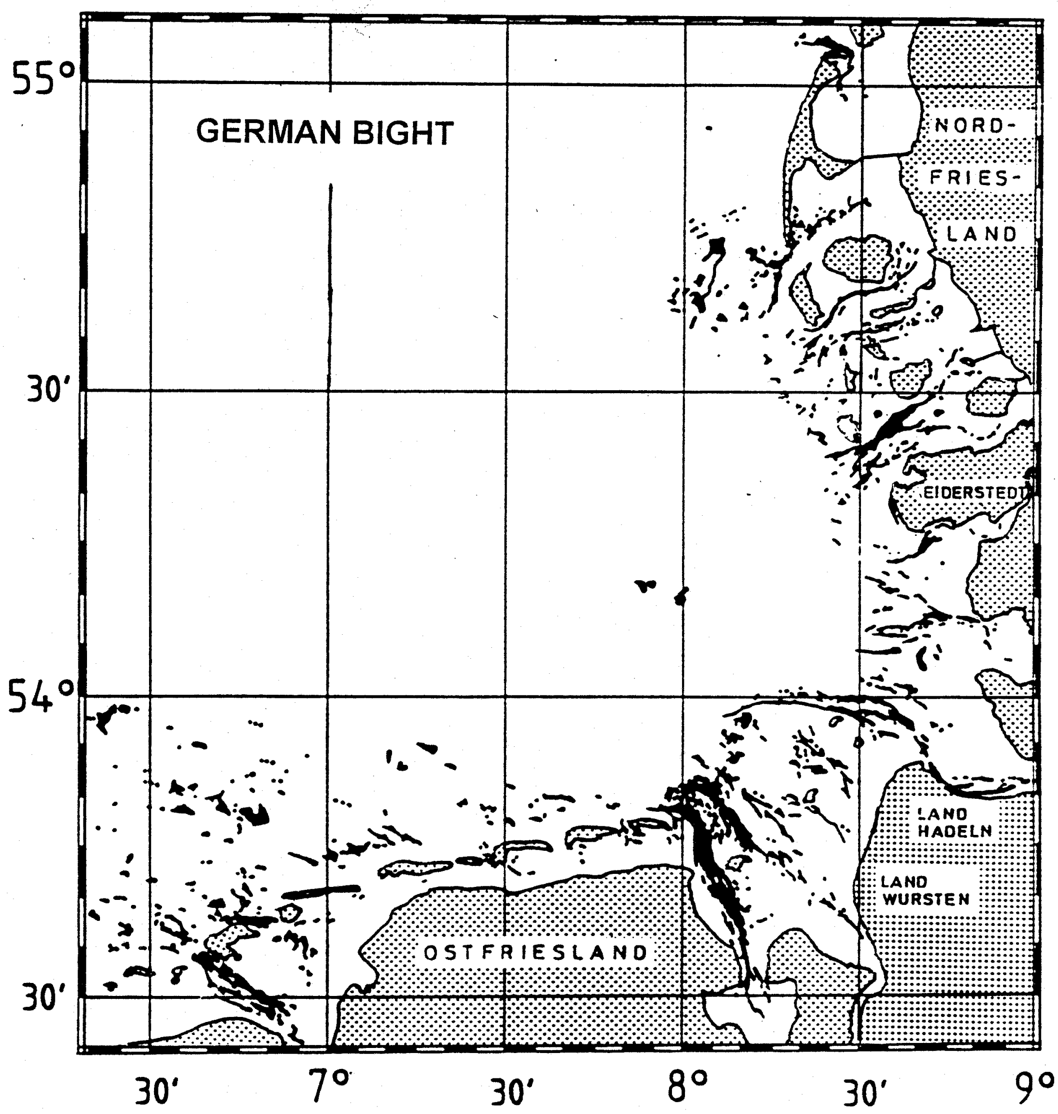

Figure 1: Distribution of tidal sand dunes in the German Bight. Modified after Ulrich (1973).

1 Instrumentation

The bedform migration process was surveyed with an array of light emitters and associated receivers at ca. 4 cm distance deployed at the sea floor. The probe was constructed to monitor at regular time intervals how far the actual sediment level rose above the seafloor (zero line at time of deployment). For this purpose light is emitted at different heights (up to 47cm) of the instrument and received after a short distance (light traps). Sensors receiving no signal are considered covered by sand. The data is recorded on photographic film. This system allows to register the migration of bedforms as a function of time. No information, however, was achievable with this system about length of the megaripples. Therefore, the absolute migration speed of the megaripples –the other unknown factor– cannot be determined. A modified system which will be used in future can record bedforms of up to 1.5 m height.

A different approach to acquire data on bedform migration is a scanning sonar mounted on top of a 5 m high tower. This tower is deployed on the seafloor. It has to be operated from a ship. This rules out the operation of the system during a storm or strong current event, the periods of highest interest when the strongest movement of bedforms is suspected to occur. A new system for the autonomous registration of the scanning sonar data is

under construction. It will be deployed in direct neighbourhood to the sensors that register the actual sediment height. With the currently used system the sea floor images allowed to measure the distance between the crests of megaripples. Their height cannot be determined with this system.
The third instrument used for the investigation of sand bedforms is a side scan sonar (100 kHz or 500 kHz) in combination with a 3.5 kHz subbottom profiler. The system is used mainly for mapping of research areas and site selection. It allows to determine the lengths of bedforms and, directly below the towfish, their height. This system demonstrated the variability of lengths and heights of bedforms occurring in a certain area.
These complex efforts to study bedform migration are required because the visual control by divers or ROVs is impossible in the research area. The reason is the high amount of suspended material in the water column. Divers can see only objects that touch their masks, i.e., zero visibility.

2 Megaripple Migration Speed

The deployment of several sand height sensors in close neighbourhood at one research site for up to 12 weeks demonstrated a strong variability of bedform migration. Some sensors were covered completely within 9-11 days and recorded no subsequent re-exposition to the water within 22 days. The heights of these bedforms exceeded the maximum recording height of the sensors (47 cm), thus prohibiting the determination of their actual heights.

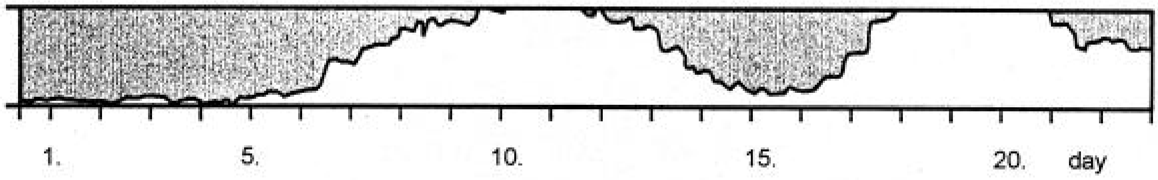

Figure 2: Recording of sand height in a megaripple field of Elbe River.. The first ripple covering the instrument has an estimated minimum speed of 45 cm/ day, the second ripple seems to have been faster and exhibits a speed of 70 cm/day (with an estimated ripple height of 50 cm, and a ripple index of 10). For a detailed discussion see text.

Other sensors recorded the repeated passage of megaripples. One example from the river Elbe is shown in Fig. 2. The passage of two megaripples is evident. During the first four days almost no coverage of sensors is recorded. Then the sensor is covered completely within five days. After 2.5 days of complete coverage the sensor is exposed to the water with a maximum exposition after 11 days since arrival of the megaripple. The shape of the curve allows to deduce further information. The high-angle lee side of a migrating bedform that buries the instrument is shorter than the low-angle luff side. One would thus expect a shorter time for the burial and a longer time for the exposition of the sensors. Here, however, the burial process took 1.5 days longer than the exposition. Obviously, an event caused accelerated bedform movement after complete burial had occurred. No height of the bedform can be given but from the shape of the curve a height of about 50 cm seems realistic. With this height and a ripple index of 10 the megaripple length is approximated as five meters resulting in a bedform speed of ca. 45 cm/day. A ripple index of 20 would result in a bedform speed of 90 cm/day. A summary of calculated bedform speed for all examples as a function of ripple index and megaripple height is given in Tab. 2.
The second megaripple buried the same sensor within two days completely and exposed it again after three more days. After another day the maximum exposition was reached on a relatively high degree of remaining coverage. The remanent coverage may result either from a general sinking of the system into the sand (this can be excluded in this case) or the temporary end of megaripple movement due to low current speeds. The latter explanation is realistic because it is observed also on a neighbouring sensor. Additional support comes from the above mentioned observation that the time for the first coverage of the sensor is longer than for the exposition. It supports the concept of higher current speeds during first exposition and second coverage. The current slowed down during/after the second complete coverage.
Based on the assumption that bedform movement was halted or slowed down to a minimum, and an on the extrapolation of the time to maximum exposition of two additional days, a 50 cm megaripple (ripple index: 10) would have had a speed of >80 cm/day. A 40 cm megaripple would still have had a speed of 67 cm/day. Again, these are minimum values because only a ripple index of 10 was assumed. For additional calculations it is referred to Tab.2
A third example is shown in Fig. 3. It was recorded in the Jade river estuary at a different time. It demonstrates an extremely fast burial and re-exposition of the sensor: within five days a megaripple of 47 cm height overrun the instrument. With a minimum ripple index of 10 (minimum bedform length: 470 cm) the minimum speed of the bedform was 94 cm/day. A more realistic bedform length results in a migration speed definitely exceeding a value of 1 m/day! This is extremely high and probably again related to a strong current event.
The next ripple (4th example) required 12 days to cross the sensor of example 3 which was still not completely re-

exposed to the water. Extrapolating to 15 days of complete passage the 40 cm high megaripple of index 10 would have had a 27 cm/day speed. Speeds are again minimum estimates because the bedform was probably higher than 40 cm as estimated from the curve.

Example	**Coverage Time [days]**	**Ripple Index**	**Bedform Height [m]**	**Bedform Length [m]**	**Bedform Speed [cm/day]**
1	11	10	0.5	5.0	45
1	11	15	0.5	7.5	68
1	11	20	0.5	10.0	90
2	6	10	0.5	5.0	83
2	6	10	0.4	4.0	67
2	6	15	0.5	7.5	125
2	6	15	0.4	6.0	100
2	6	20	0.5	10.0	167
2	6	20	0.4	8.0	133
3	5	10	0.47	4.7	94
3	5	15	0.47	7.05	141
3	5	20	0.47	9.4	188
4	15	10	0.40	4.0	27
4	15	15	0.40	6.0	40
4	15	20	0.40	8.0	53

Table 2: Summary of bedform characteristics recorded or derived in Elbe river (examples 1, 2) and Jade estuary (examples 3, 4). Sand heights data for example 1: minimum estimate, for example 2: two alternative estimates, for examples 3 and 4: measured. Period of coverage was measured. Bedform lengths and speeds are calculated for different ripple indices. A ripple index of 10 is the absolute minimum, in general a ripple index of 20 is observed in the discussed areas.

The migration speeds derived from the presented measurements are more than a magnitude higher than values for sand dunes found in the literature. Mostly, reported maximum speeds reach only a few centimetres with maximum value of a decimetre per day.

3 Megaripple Crest Movement

Langhorne (1982) showed that the crest position of a sand dune according to the nomenclature of Tab. 1 (called sand wave in Langhornes paper) oscillated with successive flood and ebb tides. Ulrich (1972) reported similar observations from the Jade estuary. The same observation was made during continuous recordings with the sand height sensors. The spikes of coverage in Fig 3 occur with a period that corresponds exactly to the tidal cycle. The sensor must have had a position in immediate neighbourhood to the crest of the bedform on which it was deployed. Identical patterns were observed also on other recordings but not always as clearly as in this example. The largest sand height differences between the different tides were recorded during the first six days when the bedform exhibits the highest migration speed as discussed above. During the passage of the next megaripple with a much lower migration speed also the tidal effects are smaller. The observations of Langhorne (1982) are fully supported by the presented continuous measurements.

In a different approach the scanning sonar tower was recently deployed on the middle of the luff flank of a sand dune having a length of 130 m in the Jade river estuary. Two 360° scans with a range of 100 m covered a circle of 200 m diameter during subsequent flood and ebb slack waters. The lee side of the upstream sand dune is clearly visible during ebb tide slack water but barely to discover during flood tide. This is interpreted to result from the backscatter fluctuations of the 330 kHz signals at the luff side that changes its slope. In addition, during three slack water situations 360° scans were made with a 50 m range. The aim was to better resolve the megaripples on the luff side of the sand dune on which the tower was deployed. The scans during subsequent slack waters allow to recognise a back and forth movement. The systems resolution is not good enough to allow a more detailed analysis.

The survey of the scanning tower site with side scan sonar revealed a mildly undulating shape of the sand dunes and a maximum angle of 30° between sand dune crest and megaripple orientation.

Discussion and Outlook

The work and data presented in this paper concentrate on megaripples. The asymmetry is indicative of a genetic environment dominated by asymmetric tidal currents. The investigated areas are, however, also influenced by waves. The deployed systems used can only observe the consequences of the effective current at the very sea floor. It is the expression of the sum of all influences. Up to now the current speed has not been measured simultaneously with the sand coverage data. This makes an interpretation of megaripple movement difficult and

causes the inclusion of several assumptions. It is not yet possible to derive an equation that relates the rate of bedform movement to current speed. As a first step two 3.5 months experiments are going on in which current meters are deployed in direct neighbourhood to the sand height sensors. This will allow to improve the understanding of bedform migration in relation to current speed. The single influence of waves and current, however, cannot be resolved. In a later step also wave rider buoys are required to estimate the wave influence in this coupled process.
The bedform speeds reported in this paper are much higher than expected from the literature. The reason is that the present study observed megaripples while the other studies monitored sand dunes. The high speed of megaripples in comparison to that of sand dunes proves that sediment transport is governed by the megaripples and not the slow sand dunes. The variable megaripple speed recorded in the Jade river within three weeks underlines the need to monitor also the many different environmental factors. Otherwise, a reliable modelling of bedform movement will be impossible.
The sand height sensor used for bedform migration analysis gave insight into the behaviour of bedform crests in a tidal current environment. The crests move back and forth with a net forward component in response to the dominant current direction. This cyclic re-organisation of crests changes the slope of the crests and luff sides both of megaripples and sand dunes. It has been monitored with acoustic methods (scanning sonar) that are sensitive to such changes.

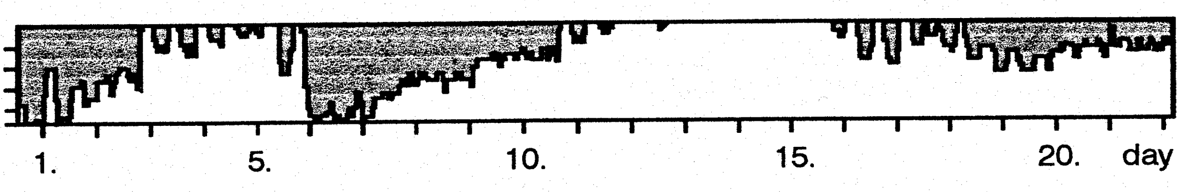

Figure 3: A 22 day example of a 12 week recording of megaripple migration in the Jade river. The first megaripple had a minimum speed close to 1 m/day. The second megaripple was slower indicating the cease of a strong current event. These strong current events are caused by the spring-neap cycles. Superimposed on the general increase of coverage is the expression of the tidal cycle that re-organised the crest depending on current direction. A detailed discussion is given in the text. The maximum height that can be recorded with the system is 47 cm (vertical axis).

The data allow to interpret sometimes a net upstream component of sediment movement (days 17 and 18 in recording of Fig. 3). This process becomes possible when major storms take a greater influence upon water movement, e.g., by pressing water into the river mouths. Events like this will soon be better understood as more relevant instruments are deployed besides the sand height measuring device.
Sediment parameters, especially grain size play an important role. Samples were always taken by geologists. A thorough analysis is not yet possible due to the lack of current measurements. In the near future this will be possible. A detailed geological sampling procedure across megaripples on one sand dune flank has been made. A strong variability has been observed so far.

Conclusions

(1) The instruments presented in this contribution allow a high accuracy at short sampling intervals for the monitoring of bedform movement in an area where diver-based work is impossible due to zero visibility.
(2) Sediment transport by bedforms happens mainly by fast megaripples that can progress by more than 1 m/day. Even faster progress is supported by the data.
(3) Crests of megaripples and sand dunes do move back and forth in response to tidal currents. This movement has (except for special conditions) a net seaward component.

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