Monitoring bedform development and distribution on a lower shoreface, central Dutch coast

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Abstract
Bedform development and distribution on the lower shoreface (14-18 m LLWS) of the central Dutch coast differ markedly between fair-weather and storm conditions. Modern observations of bedforms on multibeam sonar images confirm that unidirectional tide-dominated currents rework the lower shoreface during fair-weather conditions with significant waveheights below 2.5 m. Several Spring-Neap cycles produced straight-crested 2D-megaripples as the dominant bedform in two research areas. The megaripples are very similar to those generally observed below wave base on the inner shelf. Even minor seasonal storms (significant waveheights 3-4 m) produce an entirely different type of bedform distribution with round-crested 3D 'hummocky' bedforms (wavelength 20-40 m) and 3D-megaripples (spacing 5-8 m and 12-14 m). The bedforms observed here in a seabed of medium sands differ from those characteristic of fine sand(stone)s. Spatial differences in bedform development are partly attributed to feedback mechanisms between hydrodynamics and wave damping by the tube worm *Lanice conchilega*.

1. Introduction
1.1 Introduction
In this paper we use a broad definition of the shoreface (cf. Hill et al., 2003) and define it as the slope between the surfzone and the inner shelf, where oscillatory currents and unidirectional currents interact. Due to the shifting boundaries of wave influence in response to changing meteorological conditions, sediment transport on the shoreface is complex and episodic. Offshore and onshore fluxes of sediment vary considerably under storm, fair-weather and moderate energy conditions (Wright et al., 1991). Asymmetrical 2D-ripples develop as a response to unidirectional currents with bedload transport (cf. Ashley et al., 1990). In the shallow marine environment of the North Sea, these conditions are predicted for tide-dominated, fair-weather hydrodynamics (Van der Molen and De Swart, 2001). During storm events, increasing wind and waves cause complex combined-flow conditions under accelerating and decelerating oscillatory and unidirectional current velocities. Bed configurations change from small ripples to large ripples, and to plane bed and back, leaving a complex seabed morphology of superimposed bedforms (e.g., Swift et al., 1983; Arnott and Southard, 1990; Van de Meene et al., 1996; Li and Amos, 1999). In addition, macrobenthos may locally influence hydrodynamics, e.g. when tubes or branches extend from the seafloor into the water column and cause turbulence, or damping of wave action (DeFalco et al. 2000).

It is unknown what type of storm-related bedforms develop as a response to combined flows in medium sand, which is the dominent grain-size in the Dutch coastal zone. Humocky Cross Stratification (HCS) is mainly found in fine and very fine sand(stone)s (Walker and Plint, 1992). Van de Meene et al. (1996) analyzed sedimentary structures in 250 box cores on a shoreface-connected ridge complex West of IJmuiden and found a dominance of low-angle bedding. Some of the low-angle bedding displayed features attributed to HCS. Ancient lower shoreface deposits from the Holocene coastal barrier of the Netherlands near Haarlem (Van der Valk, 1996; Cleveringa and Schrijver, 2000), also contain horizontal and slightly inclined parallel-laminated sands with occasionally fanning of laminae, which are interpreted as deposition during upper plane bed conditions, and the inclined and fanning lamination as HCS. However, the size and geometry of HCS bedforms in the Dutch coastal zone is unknown, since the shoreface bedforms are only observed in cores.

During three surveys in 2001, bedform types and distribution, sediment composition, and macrobenthos zonation in two research areas on the Dutch shoreface were monitored within the framework of the Delft Cluster project "Ecomorphodynamics of the Sea Floor". Here we report on some new bedform types in medium sands not previously observed, and we relate the development of bedforms to wind-wave conditions, sediment composition, and macrobenthos.

2. Studied area

The shoreface west of Holland is morphologically diverse and along the central part it is characterised by a ridge-and-swale topography. The orientations of crest lines of the ridges are offset clockwise with respect to the coast-parallel tidal current. The attachment point of these shoreface-connected ridges lies on the lower shoreface at water depths between 14 and 15 m (Van Alphen and Damoiseaux, 1987). The tidal amplitude in the area is 1.5 m to 2 m. Current velocities at 1 m above the bed are typically 0.2-0.5 m/s (Van de Meene and Van Rijn, 2000). Our research areas (1 x 2.5 km) are situated within the shoreface-connected ridge complex and comprise lower shoreface to inner shelf transitions. Area 1 is part of a shoreface-connected ridge and swale, approx. 10 km West of Zandvoort with water depths 15-18 m, and Area 2 is a sloping surface landward of some shore-oblique ridges, approx. 5 km west of Noordwijk with water depths 14-18 m. The mean annual wave height measured at Meetpost Noordwijk (MPN), near Area 2, was 1.0 m in 2001 with wave heights larger than 3.5 m < 1% of the time during seasonal storms. Significant waveheights for peak storm conditions were 0.5-1 m higher at station IJmuiden (YM6), near Area 1, but similar under low-energy conditions. The dominant wind direction is from the SW, but the largest waves are generated by NW storms, which have low frequency.

3. Methods

Results of three surveys consisting of acoustic data acquisition and sample collection conducted in March/April, June/July and September/October 2001 are discussed here. Data acquisition occurred during fair-weather conditions. During the survey time no major storms occurred and the monitoring can be considered as a fair-weather survey with minor seasonal storms (windspeeds 50-60 km/h and significant wave heights of 3- 4 m). The first survey can be considered as a fair-weather situation. The second and third survey represent seasonal storm conditions (Fig. 1). Swath bathymetry was recorded using a Kongsberg Simrad EM 3000 D system, installed aboard the m.s. Arca of the State Department of Public Works. This hull-mounted system operates at a central frequency of 300 kHz and uses 254 beams. The multibeam data were obtained using 20-m track-line spacing creating a minimal overlap. Tide and velocity correction was accomplished using data collected on board and data from stations at Meetpost Noordwijk, IJmuiden and buoy MO 12 near Area 1. Relief maps were produced with oblique illumination.

Transverse bedform types in this study are subdivided into megaripples and sand waves, which represent different classes of large-scale bedforms also indicated as subaquatic dunes (cf. Ashley, 1990). Here, bedforms with wavelengths < 40 m are classified as megaripples, those with wavelengths > 80 m as sand waves. Bedforms occur as two-dimensional (2D) and three-dimensional forms (3D). The geometry of 2D-bedforms is adequately described by one transect parallel to flow, whereas 3D-bedforms are defined by three dimensions (Ashley, 1990).

Bottom samples were obtained using a cylinder-shaped box-corer with a diameter of 32 cm. Penetration varied between 0.2 and 0.3 m. Lithology, structure and sedimentological features of the sea bed were monitored in 10-cm diameter core samples covering 12 sampling stations in Area 1, and 9 stations in Area 2. Grain-size distributions (< 2 mm) of the top-lithological units were analysed using untreated samples in a Malvern Mastersizer 2000 laser particle-sizer. In March and September, duplicate sets of box-cores were acquired for analyses of macrobenthos composition.

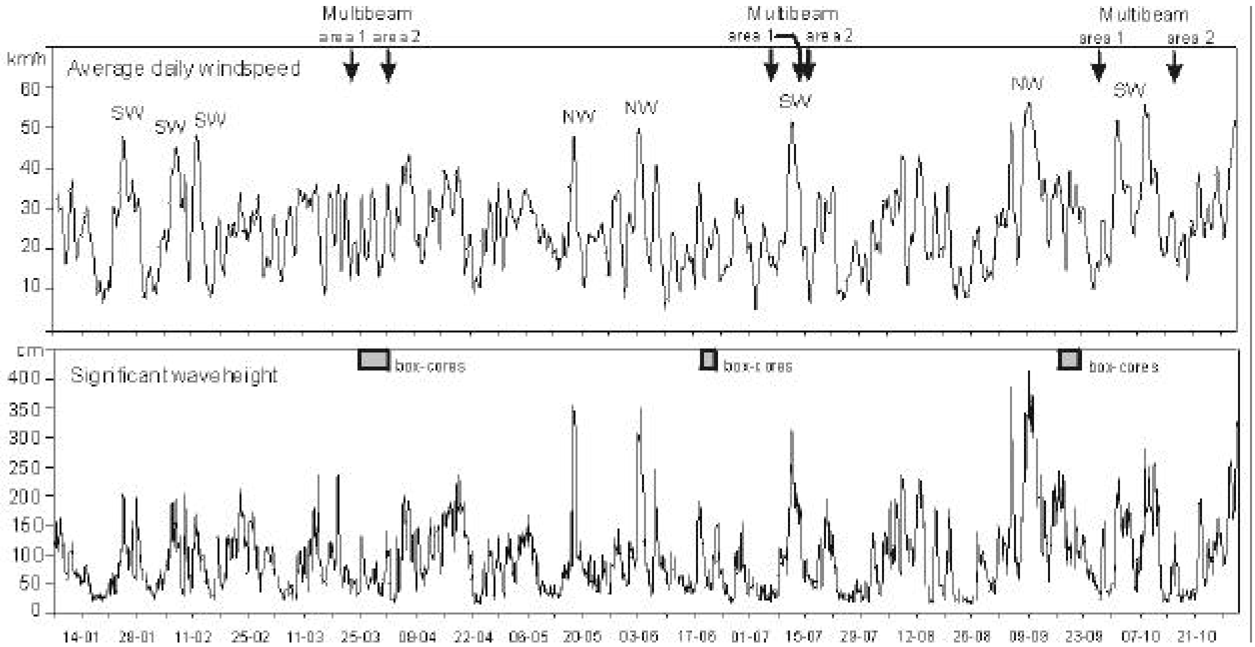

Fig. 1 – Average daily windspeed (top) and significant wave height (bottom) at Meetpost Noordwijk for the period 7 January until 31 October 2001.

4. Results

4.1 Area 1: shoreface-connected ridge near IJmuiden

Morphology and bedform distribution

The first research area comprises a shoreface-connected ridge and swale west of Zandvoort (Fig 2). Ridge morphology is characterised by a steep seaward flank and a gently sloping landward flank. Asymmetric 3D-sand waves (wavelength 700-800 m; height 1.0-1.5 m; Fig. 2), which show minor northward migration on the crest of the shoreface-connected ridge were present in all surveys. The multibeam survey of 21-22 March 2001, which is considered the fair-weather situation, yielded prominent straight asymmetric 2D-megaripples (wavelength 5-8 m; orientation 100º-105º N) covering the entire area. At the landward side of the ridge 2D-megaripples occurred superimposed on round-crested 3D-megaripples with spacing 20-30 m. At 9-10 July 2001, prior to a seasonal storm, the ridge crest and seaward area of the shoreface-connnected ridge were surveyed, but measurements were terminated because of the arrival of a the storm with winds from the southwest (average windspeed > 50 km/h; Fig. 1). The landward flank of the ridge was surveyed after the storm on 16-17 July. Prior to the storm, the seaward flank and swale were dominated by 3D-megaripples (wavelenghts 7-8 m), and the ridge crest was covered with small poorly developed near-symmetrical 2D-megaripples (wavelength 4-6 m). After the storm, the landward flank of the ridge was covered by round-crested 3D-bedforms, which were not present prior to the storm (Fig. 3). Similar 3D-bedforms were present on the landward side of the ridge during the third multibeam survey of 26-28 September 2001. Seaward of the ridge, poorly developed 3D- megaripples (wavelenght 5-7 m) were observed. Small 2D-megaripples (wavelength 4-6 m) were present on the ridge crest.

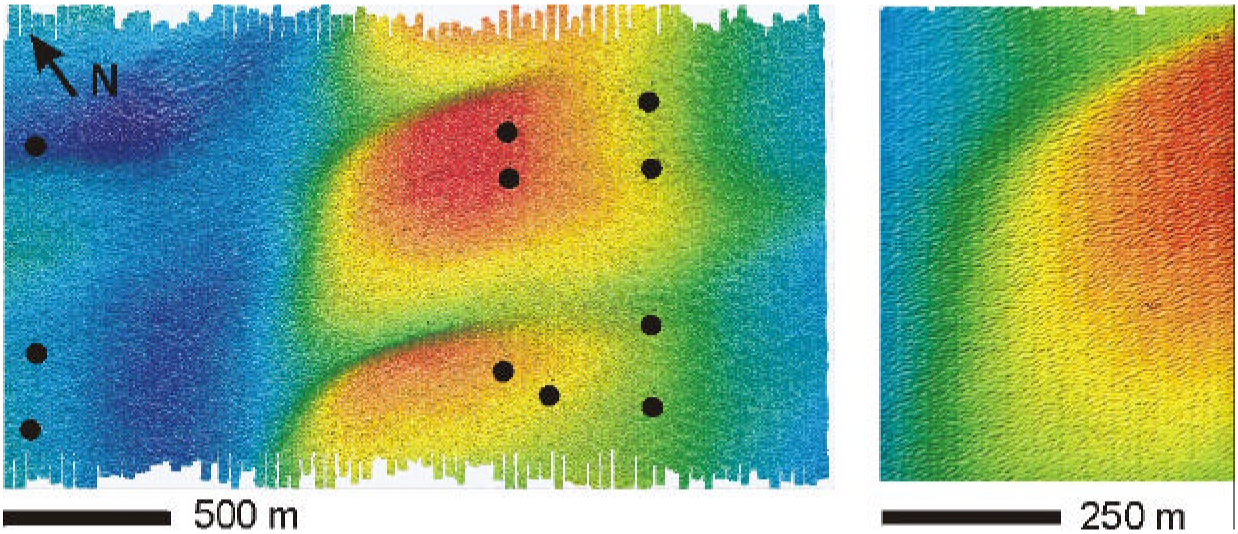

Fig. 2 – Multibeam swath bathymetry of Area 1 near Zandvoort processed with artificial oblique illumination. Left image based on data collected 9-10 and 16-17 July, right image with 2D-megaripples at 21-22 March 2001. Black dots are box-core sample locations.

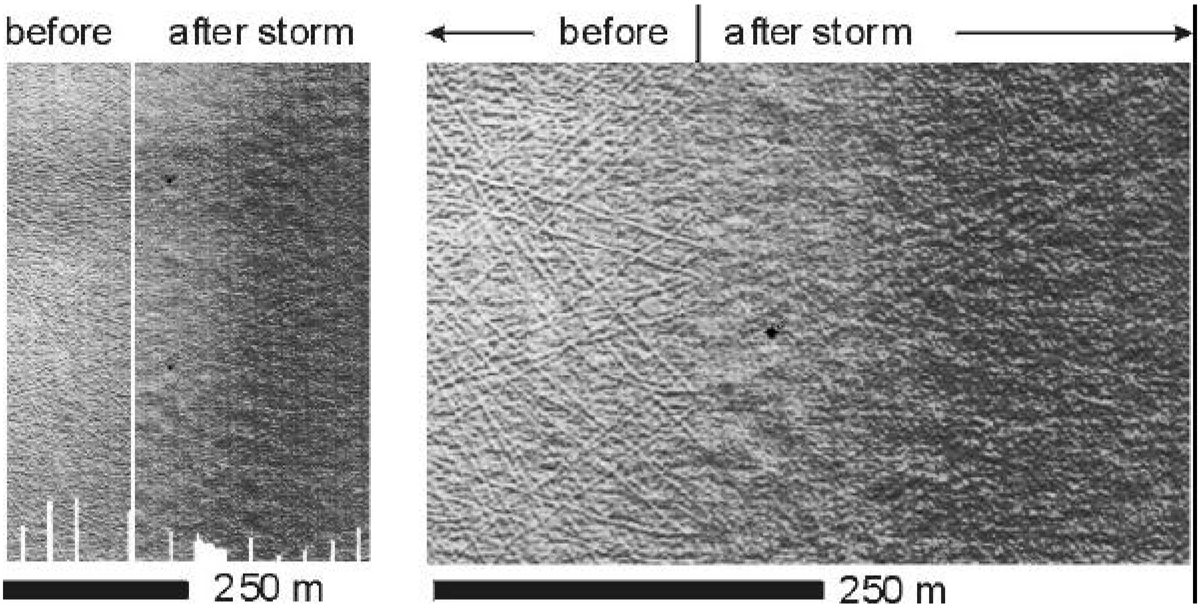

Fig. 3 – Multibeam swath bathymetry of part of Area 1 with artificial oblique illumination., based on data collected 9-10 and 16-17 July, before and after a SW storm (see Fig.1). Black dots are box-core sample locations.

Sediment composition and macrobenthos

In Area 1, sediments consisted of uniform, cross-bedded, and graded sands with shell fragments. Most cores displayed uniform lithologies, although increasingly more cores with stratified sediments were recovered in June and September. Approximately half the cores had visible burrows, but no seasonal trends were observed. Cores from the swale seaward of the ridge lacked distinct structures, those from the crest of the ridge had a uniform structure and color, with occasionally lags of coarser sand and shell fragments. Cores from the landward side of the ridge displayed low-angle crossbedding, horizontal bedding, and coarse lags. For March, the median grain-size (D50) of the seabed sediments on the ridge ranged from 319 to 366 µm, those in the seaward swale were 300-310 µm. In June and September 2001 a general fining of the sediments to median grain-size ranges of 281-346 µm had occurred, both on the ridge and in the swale. Macrobenthos consisted predominantly of segmented polychaete worms, such as *Nephtys sp*., and *Scoloplos armiger* (Baptist, 2002). In addition, *Urothoe poseidonis* and *Echinocardium cordatum* were characteristic for the ridge crest. In September, the mollusc *Ensis americanus cf. directus* was dominating in the swale.

4.2 Area 2: lower shoreface near Noordwijk

Morphology and bedform distribution

The research area on the lower shoreface west of Noordwijk has a concave profile with a steep upper part (1:400) and a swale. Seaward of the swale are two very low shore-oblique ridges, which fall outside the survey area. At 2-3 April 2001, during the fair-weather survey, the seaward part of the area was characterised as an irregular pattern of round-crested 3D-megaripples, covered with symmetrical and asymmetrical 2D-megaripples of wavelength 4-8 m (Fig. 4). Megaripples were fading in shoreward direction, and round-crested 3D-megaripples with spacing 20-30 m were present in water depths of 15-16 m nearest to the shore. At 17-19 July 2001, after a seasonal storm, bedforms in the seaward swale were characterised as round-crested 3D-bedforms spaced at 30-40 m with superimposed 3D-megaripples (spacing 12-14 m). Some linear furrows in the seaward swale, produced by trawl fishing, were still visible after three months. In July, severe trawl-fishing activities inhibited observations on bedforms nearest to the shore. The third multibeam survey took place on 15-16 October 2001. Bedforms were of a complex symmetrical and asymmetrical 3D-megaripple type (wavelength 11-13 m; Fig. 4), that slightly increased in size in offshore direction, but covered the entire research area.

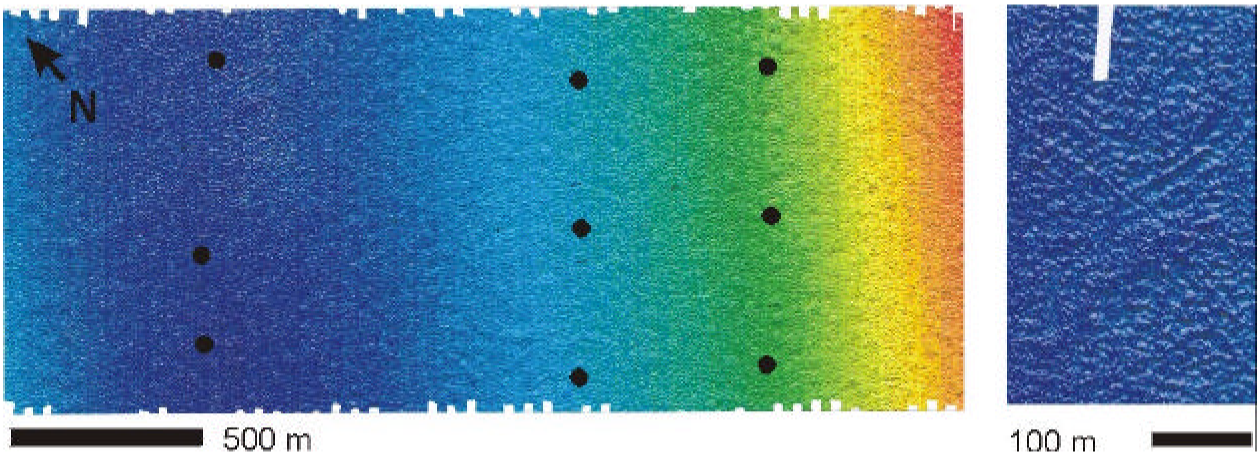

Fig. 4 – Multibeam swath bathymetry of Area 2 near Noordwijk processed with artificial oblique illumination. Left image based on data collected 2-3 April, right image with 3D-megaripples on 9-10 July 2001. Black dots are box-core sample locations.

Sediment composition and macrobenthos

Seabed sediments from the lower shoreface were extremely variable and comprised uniform sands, shelly sands, and laminated sand and clay. Most of the sediments were stratified and displayed sharp contacts, which could be attributed to erosion. Flaser bedding was encountered in one core collected in March. Several cores collected in June and September 2001 had uniform, a few cm thick, oxidised tops with polychaete tubes extending from the surface. Two cores collected in June displayed homogenised muddy, organic sands with rip-up clasts of laminated clays. Other cores consisted of undisturbed rhythmic cm-sized fine sand and clay laminations, especially in June. The median grain-size of sea bed sediments decreased from 261-328µm in March to 235-299µm in September and became more poorly sorted. In March, segmented polychaete worms, such as *Scoloplos armiger* and *Nephtys sp.*, were dominant throughout Area 2, but *Urothoe poseidonis* was also characteristic for the swale (Baptist, 2002). In September, *Lanice conchilega* and *Ensis americanus cf. directus* were dominant through Area 2, although the two species were far more abundant in the swale than on the slope.

5. Discussion and conclusions

5.1 Bedforms of fair-weather conditions

The first survey of March-April occurred after a 3-month period of fair-weather conditions with average significant wave heights of 0.8 m and not exceeding 2.5 m at MPN. The last storm with significant waveheights > 3 m was in December 2000. Straightcrested 2D-megaripples are generally best developed in the seaward end of the research areas and fade in landward direction. The wavelengths of the 2D-megaripples (4-8 m) correspond to megaripple wavelengths in sediments of comparable grain-size below wave base on the inner shelf (Passchier, this volume). In cores taken west of IJmuiden, Van de Meene et al. (1996) found an increase in low-angle and horizontal bedding in the shoreward direction coinciding with fading of 2D-megaripples. The most likely explanation for the gradual change in bedforms is a shoreward increase of the overal influence of wave-induced oscillatory flows on sediment transport. Asymmetrical transverse bedforms are generally interpreted to be related to bedload transport under unidirectional currents (Ashley, 1990). Sediment transport observations on the shoreface-connected ridge during spring tidal, fair-weather conditions by Van de Meene and Van Rijn (2000) have shown that sediment transport rates (predominantly bed load) are very low and occur episodically during a period about 2 hours around maximum spring tidal flow. Measured near-bed (0.45 m) current velocities during sediment transport were 0.4 m/s. The 2D-megaripples we observed are probably related to tide-dominated bedload transport, but these measurements suggest that under fair-weather conditions these bedforms can be considered relatively stable between spring flood maxima. The flaser bedding preserved in one of the box cores is in agreement with these conclusions. However, spatial differentiation in the development and dynamics of 2D-megaripples is also apparent. Observations of side-scan sonar and multibeam images of the 26 July and 26-28 September, collected 1-2 weeks after a storm, reveal that 2D-megaripples already developed on the ridge crest within one Spring flood event. At ridge crests, these bedforms seem to be active witin a broader window of conditions, probably related to the presence of the 3D-sand waves.

5.2 Bedforms of seasonal storm conditions

Three types of 3D megaripples were encountered in this study. The three types of 3D-megaripples originated as a response to different flow conditions. The round-crested 3D-megaripples with spacing 20-30 m we observed shoreward of the shoreface-connected ridge after seasonal storms are related to high oscillatory flows, which becomes more dominant when wave base descends to the lower shoreface. In the seaward swales of Area 2, roundcrested 3D bedforms (30-40 m) are also present after fair-weather conditions and have superimposed bedforms. Preservation of beamtrawl tracks between surveys shows that sediment mobility there is low. These bedforms are likely inherited from previous major storm events with wave base extending down to larger water depths than the storms recorded in 2001. The large 3D-megaripples (spacing 11-14 m) developed during the seasonal storms in greater water depths, where minor currents may have influenced their geometry. However, the smaller 3D-megaripples with wavelength 5-8 m in Area 1, which were observed twice in the upcoming phase of a seasonal storm with winds from the southwest, may have originated as a response to a wind-increased flood current, with minor influence of oscillatory flow. Analysis of wind- and current data from Meetpost Noordwijk (Van de Meene & Van Rijn, 2000) indicate that southwestern winds (180-210ºN) of 36 km/h resulted in 10% increase (54 km/h in 20% increase) of shore-parallel currents during the north-going flood.

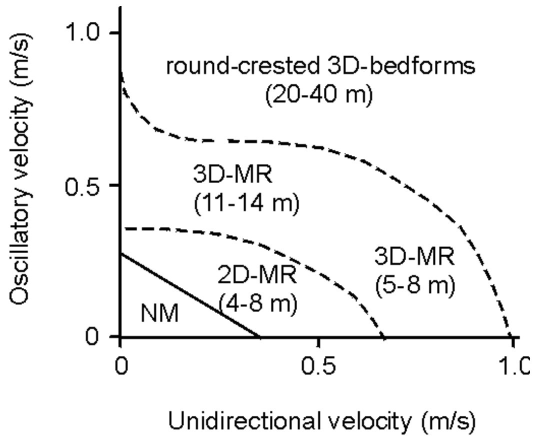

Fig. 5 – Bedform types in medium sand observed in Areas 1 and 2 presented in a graph of estimated near-bed unidirectional velocity vs. orbital velocity (Modified from Arnott and Southard, 1990). Orbital velocities were calculated using linear wave theory and data from MPNand YM6. Unidirectional velocities were estimated based on measurements in Van de Meene (1994).

Most scientists accept the interpretation that 3D-ripples occur under larger flows than 2D-forms for a given depth and grain-size (Ashley, 1990). However, opinions vary as to the contribution of oscillatory flows in the formation of different types of 3D-megaripples. Swift et al. (1983) observed 3D-megaripples of 2-5 m spacing on the inner Atlantic shelf after storm conditions and interpreted them as bedforms formed under combined flow, which are preserved in the geological record as HCS. Other types of 3D-bedforms are also reported: round-crested 3D-megaripples of 1-5 m wavelength have been observed in the Atlantic surfzone during fair-weather conditions (Gallagher, 2003). In flow-duct experiments, large 3D-ripples of >2 m spacing were generated in fine sands, and bedform spacing increased dramatically with increasing oscillatory currents (Arnott & Southard, 1990). In purely oscillatory flow of 0.4-0.8 m/s, the 3D-ripples were characterized as symmetrical undulating bed topography. These observations are comparable to ours in medium sands and modern environments and show that 3D bedforms develop under a range of flow conditions, which produce 3D ripples of distinct geometries and wavelengths (Fig. 5).

5.3 Influence of macrobenthos

Under similar meteorological conditions, bedforms are generally more poorly developed in Area 2 than in Area 1 and surficial sediments in Area 2 are finer and more poorly sorted than those of Area 1. For storm conditions, the difference can be partly explained by 0.5-1 m higher significant waveheights measured at station IJmuiden relative to MPN. Although hydrodynamics are the primary control on bedform development, different seabed characteristics and macrobenthos assemblages may also influence size, geometry, and preservation of bedforms. The finer and more poorly sorted surficial sediments in Area 2 in June and September could be solely related to hydrodynamics forced by the increased stormyness of these surveys relative to the April survey. However, the changes in seabed characteristics also coincide with the presence of *Lanice conchilega* communities on the sea floor. In anology to seagrass studies in the Mediterranean (De Falco et al., 2000), coverage of the sea floor with *Lanice conchilega* may result in damping of wave action and trapping of fine particles, so that sediments become finer and more poorly sorted than in areas not covered by tube worms. Although the higher abundance of *Lanice conchilega* in Area 2 could have occurred in response to lower significant wave heights compared to Area 1, damping of wave action could be a possible positive feed back reinforcing the differences in bedform development between the two areas. The hypothesis will be tested when analyses of 2002 are complete.

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