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Intertidal bar dynamics

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Abstract

Intertidal bars are non-permanent features. The morphologic characteristics and environmental settings of intertidal bars are presented. The most optimal environmental conditions for intertidal bars are those related to semi-enclosed coastline with a micro to meso tidal range and an alternation of storm and non-storm conditions. The short-term behaviour of these intertidal bars are reviewed with special emphasis on the different phases in their behaviour: the generation, evolution and decay. The succession of their phases on longer time spans is studied with attention to the sequences of intertidal bar states. Finally, the net response of the intertidal bars on the berm development is discussed.

1 Introduction

Intertidal bars are common features on many sandy beaches along wave dominated and fetch-limited shores. Their presence influences the sediment budgets on the beach and protects the shoreward located dunes against erosion. However, most of the intertidal bars are non-permanent features. Their occurrence is closely related to the offshore wave conditions with no bars during storms and bar generation in the post-storm recovery stages.

In the next section a review is given about intertidal bar environments and types on wave-dominated unprotected coastlines. Besides, the short-term dynamics of the intertidal bars at specific sites along the coast of the Netherlands are described. Finally, these short-term dynamics with sequences of phases is discussed in relation to the long-term development of the beaches.

2 Background

General environments of intertidal bars

Intertidal bars only occur under a combination of factors. These factors are the wave conditions, tidal range, nearshore slope and sediment characteristics. The wave conditions for intertidal bar occurrence are optimal with a finite limit of the wave period and breaker height, controlled by a limited fetch. The tidal range especially determines the volume of the intertidal bar and related migration rate. The nearshore slope is optimal in case of a wide foreshore with a moderate to low gradient (e.g. King and Williams, 1949; Owens, 1977; Orford and Wright, 1978; Davis et al., 1972; Owens and Frobel, 1977).

Besides, two boundary conditions are also of importance for the occurrence of intertidal bars: the type of wave climate and the beach state. Allen (1985) distinguished three types of wave climate conditions:

1) the strong seasonal dichotomy in wave climate with winter erosion and summer deposition, like on the West Coast of the USA;
2) the dominating and catastrophic control of hurricanes, like on the Gulf Coast of the USA;
3) the succession of storm and non-storm conditions, like on the Atlantic beaches of the USA, the coastlines of the Great Lakes and along the North Sea.

The major changes in beach morphology at (1) are related to berm steepening and flattening over the year (e.g. Strahler, 1966; Sonu, 1973; Felder and Fisher, 1980). A small intertidal bar only occurs during low energy conditions. Sonu and Van Beek (1971) even stated that the berm development is a sort of intertidal bar development without a shoreward slipface. The beaches at (2) mostly lack any intertidal barred feature. The beaches at the coastlines with a succession of storm and non-storm conditions (3) are among the most favourable for the occurrence and cyclic development of intertidal bars (e.g. King and Williams, 1949; Davis et al, 1972; Owens and Frobel, 1977; Nordstrom, 1980; Kroon, 1994).

The beach state model of Wright and Short (1984) clearly stated that the intertidal bars on the beach are best developed during low to moderate energy wave conditions in their 'Ridge-and-runnel or low-tide terrace' state. Intertidal bars do not occur during highly dissipative conditions (see many Australian papers) nor during fully reflective conditions.

Intertidal bar types and their characteristics

An intertidal bar or ridge (King and Williams, 1949; Orford and Wright, 1978) is a body of sediment on the intertidal beach that is mainly the result of swash and backwash processes. Therefore, these ridges are also called swash bars. However, the strict definition of swash bars says 'that they develop during flood tides in areas with a limited fetch' (King and Williams, 1949; Owens and Frobel, 1977). This implies that intertidal bars may also be called swash bars when they occur above mean sea level. Two types of intertidal bars occur in the classification of Wijnberg and Kroon (1998): the low-amplitude ridge and the slip-face ridge.

The low-amplitude ridge is observed on beaches with a macro tidal range accompanied by a limited fetch for short waves, and a flat sloping beach (in the order of 1:60 or less). These ridges are small features with a height of some decimetres, a width of some metres and a length of hundred of metres (Short, 1991). The corresponding volume of a ridge is rather small and in the order of 1 to 5 m^2.m'. A shoreward slip face of the ridge is mostly absent. These small ridges are the same as the small lenses of sediment with a low amplitude (max. 0.25 m), no slipface and a shoreward migration rate of 2 to 3 days as observed by Owens and Frobel (1977). The alignment of the ridges corresponds to the waterline. If the intertidal beach is wide enough, multiple longshore ridges can be observed on the beach, with more or less permanent ridges along the mean neap low-water line and the mean neap high-water line (King and Williams, 1949; Short, 1991). Multiple ridges are supposed to be remnants of equilibrium slope adjustments at different tidal stages. The profile remains especially fixed in position with hardly any adjustment in the mid-tide zone of swash and backwash (Strahler, 1966). The depressions at the shoreward site of the (multiple) alongshore ridges are called the runnels. These runnels drain the water off the beach during falling tide. Only in cases of a distinct ridge on the seaward side of the runnel, the runnel may behave like a feeder channel.

The slip-face ridge is observed on beaches with a micro- to meso tidal range with a moderate to steep sloping beach (with gradient values over 1:60). These ridges are often larger than the previous described features. During their maximum development, the height of the ridge is of the order of 1 to 2 metres, the width is of the order of 10 to 50 metres and the length may reach values up to 100 m (Kroon, 1994). These ridges are the same as the well defined slip face ridges with an amplitude of 0.50 to 0.75 m, a width of 25-30 or 40-50 m and a shoreward migration rate of 2 to 3 days over the intertidal beach as observed by Owens and Frobel (1977). The corresponding volume of the ridge is in the order of 10 to 50 m^2.m'. The ridges are also aligned with the waterline and may, for instance, follow the curvature of larger beach features like low-tide terraces and embayments (Kroon, 1994).

The depression between the ridges and the berm or between a ridge near the low-tide mark and a ridge near the high-tide mark is also called runnel or feeder channel. This feeder channel is shore-parallel aligned and drains the water during falling tide. At distinct locations along the beach, the water of the feeder channel drains through the ridge in the cross-shore direction through a rip channel. This rip channel may have a shore-normal or oblique orientation to the local shoreline. The shore parallel spacing of these intertidal rips are irregular and changes with the offshore wave energy conditions. However, the rips on the intertidal beach are often less permanent and the spacing is always smaller than those observed in the subtidal zone (Short, 1985). The position of the slip-face ridges on the intertidal beach is of importance for the process characteristics. The ridges on the upper part of the beach near the water line at high-tide and close to the berm (high-tide ridges or swash bars) are dominated by the swash and backwash during flood. At ebb, these ridges are subaerial. The ridges on the lower part of the beach near the water line at low-tide (low-tide ridges) are dominated by swash and backwash during ebb, and wave related processes, like wave asymmetry and wave breaking during flood.

3 Field sites

The field sites were located along at the central part of the Holland coast near the villages of Noordwijk and Egmond (Figure 1). The morphologies of these sandy shorelines were characterised by two subtidal bars in the nearshore and one or two intertidal bars on the beach (Figure 2). The outer subtidal nearshore bar was almost shore parallel and straight crested. The crest of this bar was about –3 to –6 metres below mean sea level. The inner subtidal nearshore bar was often crescentic with a crest at about –1 to –3 metres below mean sea level. The crescentic features had a longshore dimension of about 500 metres. The cross-shore spacing between the nearshore bars was about 300 metres. The subtidal nearshore bars were permanent features with a net seaward migration of some 100 metres a year. The intertidal bars were non-permanent features.

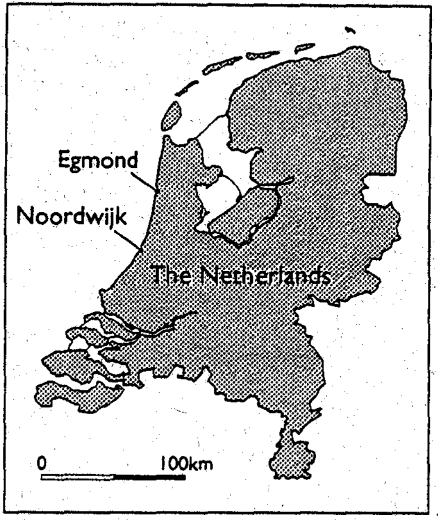

Figure 1 *Location of the field experiment sites in The Netherlands*

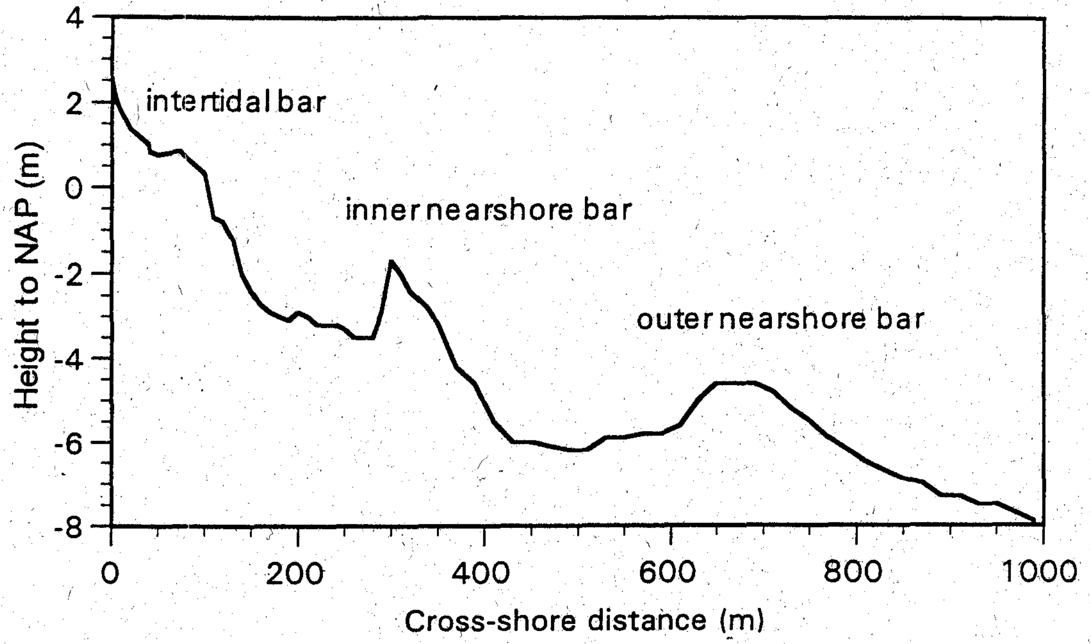

Figure 2 *A barred cross-shore profile at the Egmond site*

The mean slope of the intertidal beach varied between 2 and 7°. The intertidal slope was gentle under high-energetic dissipative wave conditions and steep under low-energetic reflective wave conditions. The sediments of the sandy intertidal beach had a mean grain size between 0.25 and 0.35 mm, which corresponded with a range of fall velocities between 0.03 and 0.055 $m.s^{-1}$. The median fall velocity (ω_s) at the crest of the intertidal bar was 0.034 $m.s^{-1}$.

The offshore conditions at the Holland coast represent a mixed-energy coast of a semi-enclosed sea. The incoming waves have an annual mean wave height of about 1.3 metre and come from south-western to north-western directions. The semi-diurnal tidal range is about 1.65 m, with a spring-tide range of about 2.1 m and a neap-tide range of about 1.4 m. The tidal curve is asymmetric with a 4 hour flood period and an 8 hour ebb period.

4 Data set and methods of analysis

Data set and measurement techniques

The data set of the morphology consisted of cross-shore levelled profiles and video-images (Noordwijk beach only). The cross-shore profiles at the intertidal beach were levelled from the dune foot to the wading depth with a levelling instrument and a stake. The cross-shore spacing between the measurement points was irregular and depended on the variability in slope. The video-images at Noordwijk beach showed an oblique snap shot and an oblique time-exposure (averaged light intensities over 12 minutes) over a longshore beach length of about 2 km. These oblique images were converted to a plane view with the use of metric equations and ground control points on the beach and in the dunes.

The data set of the offshore hydrodynamics consisted of hourly measured 10 minutes averaged wave variables (significant wave height, wave period, wave direction) and water levels. The wave variables were recorded with wave buoys at IJmuiden (20 km offshore), Egmond (2 km offshore) or Noordwijk (7 km offshore). The water levels were locally measured at the beaches and at the nearshore stations IJmuiden and Petten with the use of a water level staff along a measuring pole.

Methods of analysis

The cross-shore profiles were used to measure the morphometric variables of an intertidal bar as presented in Figure 3. These variables included the position of the bar crest, the height of the bar crest to NAP, the width of the bar and the slopes of the bar.

The offshore wave heights were transformed from deep to shallow water with the use of a wave energy decay model (see Battjes and Stive, 1985). The water levels at Egmond were taken as the mean values of those measured at IJmuiden and Petten.

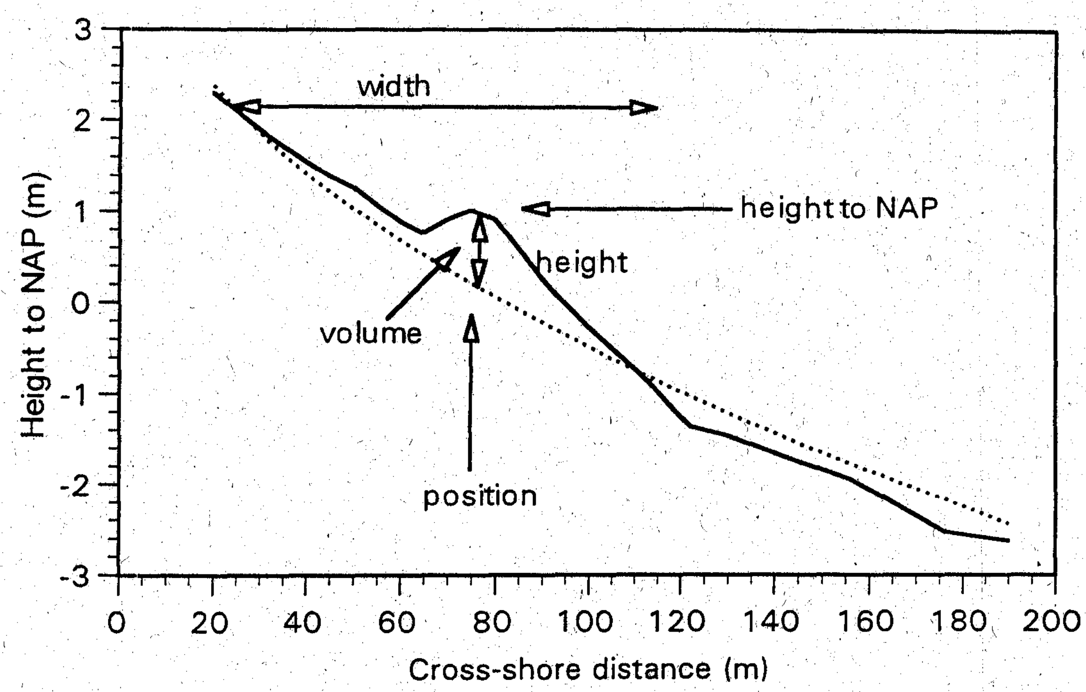

Figure 3 *Definition sketch of morphometric variables of an intertidal bar. Dotted line is the mean profile (see Kroon, 1994).*

5 Results

The general behaviour of the intertidal bar on the Egmond beach is presented in Figure 4. The morphometric variables like bar crest position, bar crest height to NAP, bar width, bar height, asymmetry of the bar and bar volume were followed over a couple of weeks. This period was split in four parts, all with

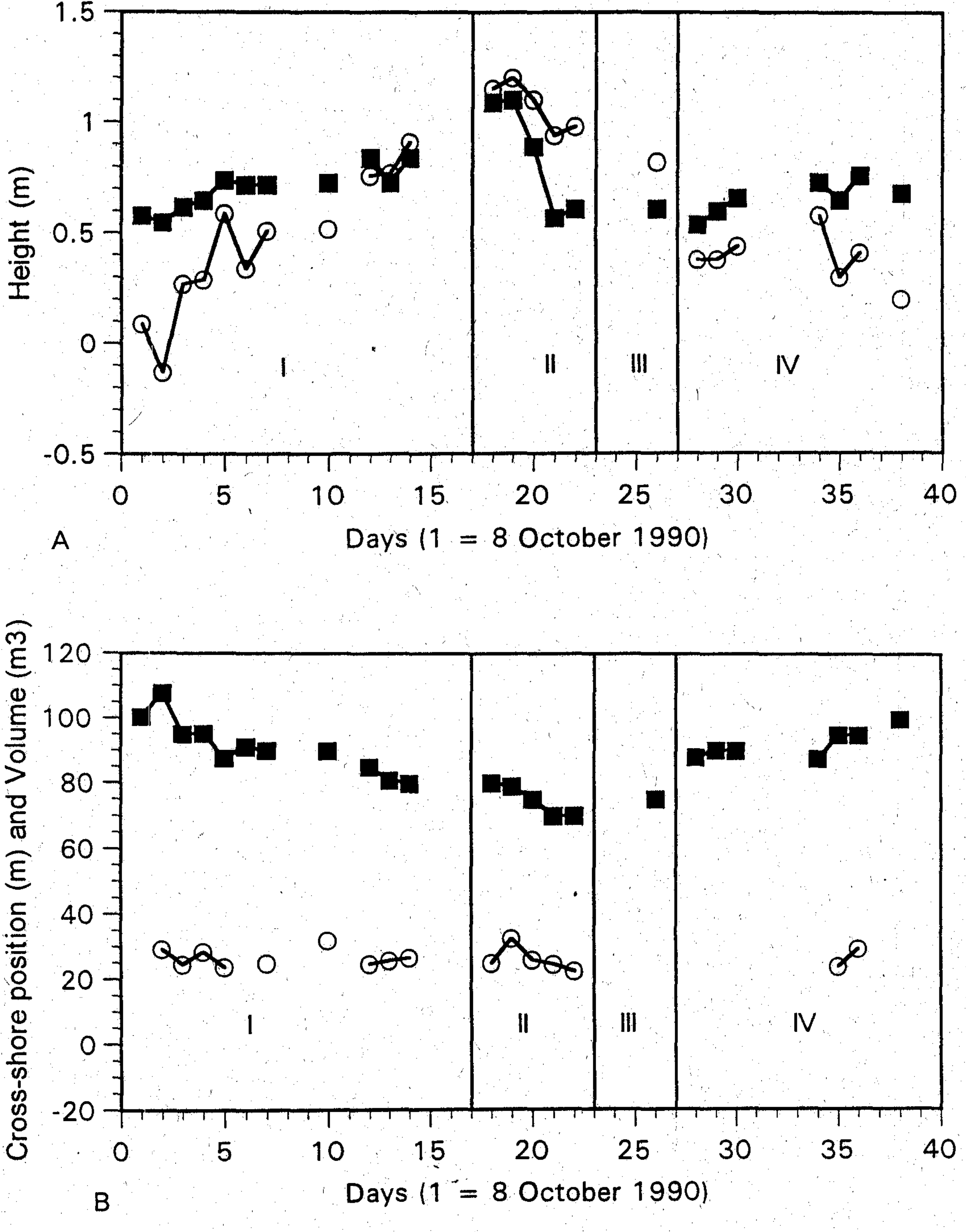

Figure 4 *Timeseries of a) intertidal bar heights (squares) and heights to NAP (circles) and b) cross-shore positions (squares) and volumes (circles) at Egmond beach.*

their own characteristics. In the first period (I) the intertidal bar developed. The crest of the intertidal bar increased in height from 0.5 to 1.1 m and migrated in the direction to the dunes over 40 m. The absolute height of the crest increased from –0.2 m NAP to +1.2 m NAP. The width of the bar was between 80 and 90 m. In the second period (II) the fully developed intertidal bar slightly eroded. The intertidal bar faded and the maximum heights decreased to 0.5 m at +0.4 m NAP. The third period (III) showed a further flattening of the intertidal bar. This was especially observed in the seaward migration of the bars crest. The fourth period (IV) showed again an intertidal bar that hardly grew.
One type of relation was obvious, a positive relation between the bar crest height to NAP and the bar crest position onshore (Figure 5).

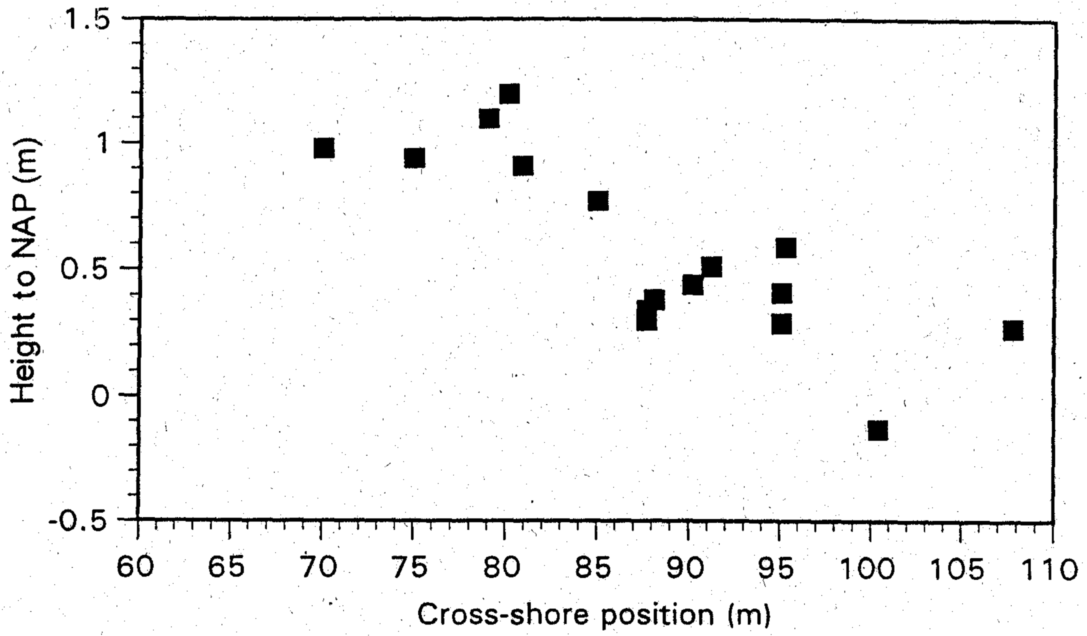

Figure 5 *Cross-shore position of the intertidal bar versus the height of the crest to NAP at Egmond*

The general behaviour of the intertidal bar on the Noordwijk beach is presented in Figure 6. Both the intertidal bar crest position and height showed the same tendencies as at Egmond.

The longshore consistency of the intertidal bar patterns was observed in the video-images at Noordwijk (see Figure 7). The intertidal bar behaved pretty uniform along the coast and was only following the larger morphological units like horns and embayments.

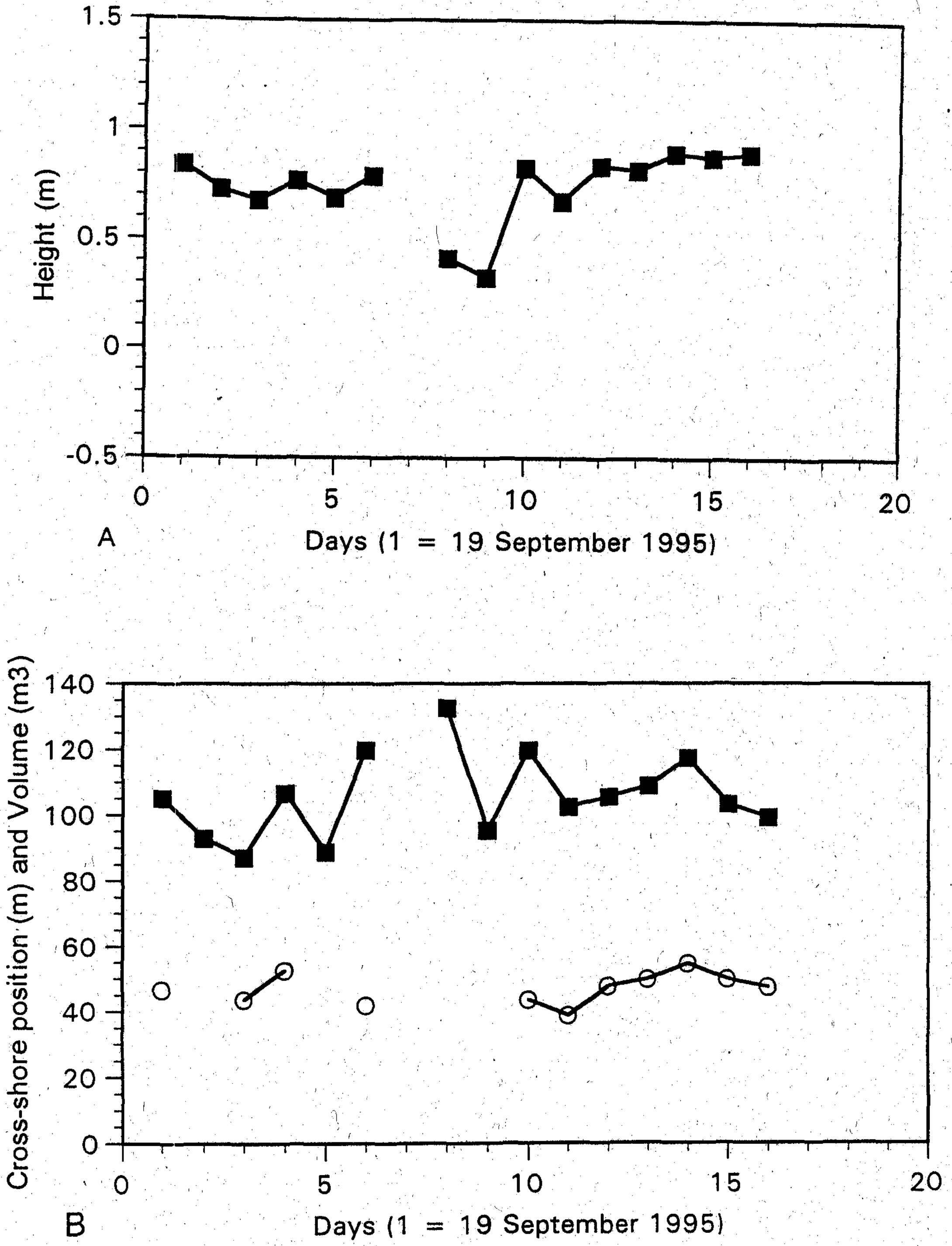

Figure 6 *Timeseries of a) intertidal bar heights (squares) and b) cross-shore bar positions (squares) and volumes (circles) at Noordwijk*

The morphological changes were coupled to the offshore wave conditions. Both at Egmond and at Noordwijk, the offshore collected wave data were used in an energy decay model over the measured cross-shore profiles to shore. In this way, the significant wave heights over the inner nearshore bar were

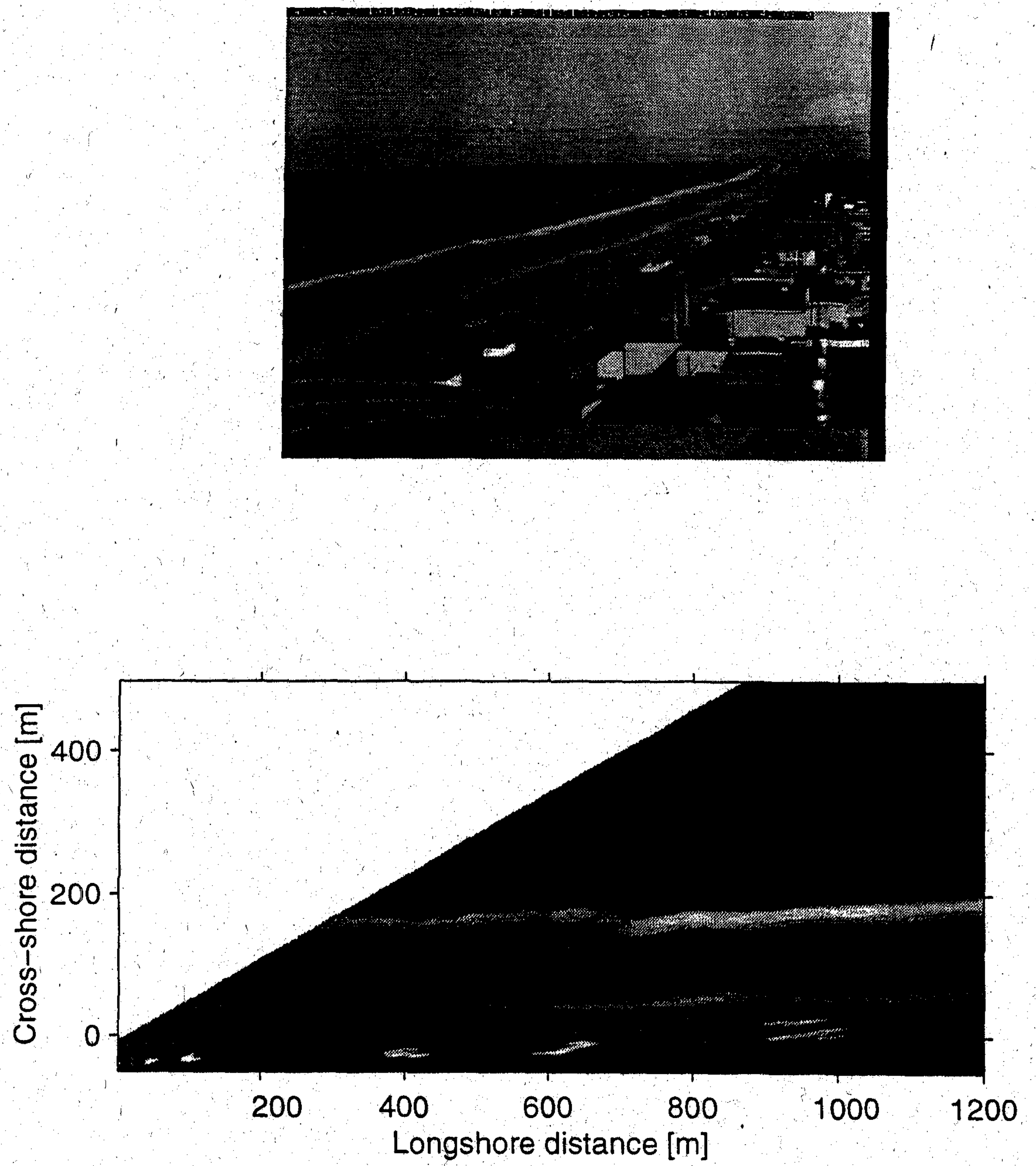

Figure 7 *Intertidal bars at Noordwijk in a) oblique view and b) plane view on 23 September 1995*

computed. The local relative wave height at the inner nearshore bar, defined as the local significant wave height divided by the local water depth, is presented over time in Figure 8. It is obvious that an erosion of the intertidal bar and aflattening of the beach can be related to an increase in local relative wave heights, whereas a decrease in local relative wave height was accompanied by a growth or landward migration of the intertidal bar.

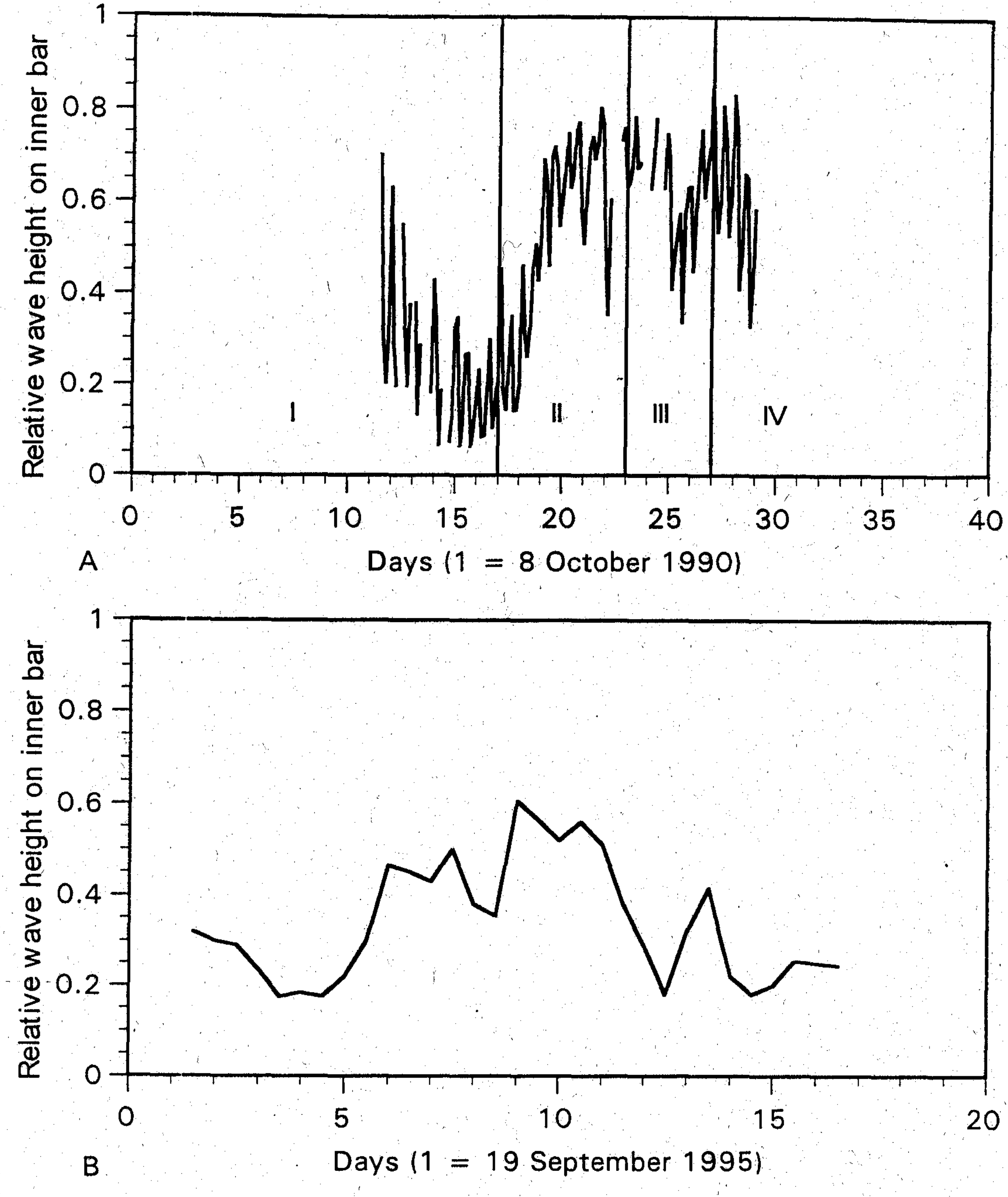

Figure 8 *Relative wave height at the inner bar at a) Egmond and b) Noordwijk beach*

6 Discussion

Intertidal bar dynamics

Phases in bar behaviour

All types of intertidal bars are non-permanent features. Their life time may vary from just a couple of days to a couple of months. In general the intertidal bar behaviour is split in three phases: the generation phase [initial generation and growth] (I), the evolution phase [migration and stabilisation] (II) and the decay phase [flattening or merging](III) (see also Davis et al., 1972, Dabrio and Polo, 1981, Mulrennan, 1992, Kroon, 1994). However, these phases do not always succeed in time (see Figure 4). The succession of phases of an intertidal ridge under low-energy wave conditions could be a generation on the intertidal beach followed by a migration during successive floods in a shoreward direction to the high water mark. As soon as the ridge is at the high tide mark and merges to the berm, another ridge may already be formed by the low-tide mark and migrates to the berm again. The berm widening and heightening is the net effect of these successive ridge merging (Kroon, 1994). This often happens during the calm summer season in the Netherlands. The beach is then building its sediment buffer for the next 'winter' storms and the cross-shore beach profile develops into its 'summer' profile. The succession of phases of an intertidal ridge under high-energy wave conditions may be a continuously decay of the ridge. This implies that the intertidal beach flattens and further lowers. There might be no time for a ridge recovery between the storms. The berm will be demolished. This happens often in two modes, as removal due to the return flows descending on the beach face as the over-washed water is drained from the runnel area, or as the formation of a scarp due to direct scouring by waves (Sunamura, 1988).

Generation mechanism

Hayes and Boothroyd (in Owens and Frobel, 1977) and Davis et al. (1972) suggested a ridge formation in relation to storm activity. During the storm the beach erodes, becomes planar or concave and the sediment is deposited in the low tide area. The days following storm subsidence there is an initial modification of the beach profile and two types of ridges may develop (Owens and Frobel, 1977). These ridges are a low-amplitude ridge that rapidly grows, migrates shoreward and welds to the berm, and a slip-face ridge that is simultaneous constructed on the low-tide terrace. This slip-face ridge may also migrate in the shoreward direction in a later phase. The exact mechanism of ridge initiation is still unknown. However, the swash and backwash processes mainly generate ridges with a more or less stagnant water level on the beach over a certain period. The shoreward directed swash velocity near the bed exceeds the seaward directed back wash velocity due to the wave asymmetry effect and due to the effect that part of the water volume of the swash infiltrates into the beach and will not flow seawards as back wash. On beaches with a flat to moderate slope, these net differences between swash and backwash may result in ridge formation near the water level. On steeper beaches this process leads to the direct development of a berm (Strahler, 1966; Sonu and Van Beek 1971).

A generation mechanism related to the infragravity waves for the multiple low-amplitude ridges in a macro-tidal environment is proposed by Simmonds et al. (1997).

Evolution of intertidal ridges

Just after the initiation of an intertidal ridge, the slip-face ridge may grow, stabilise and/or migrate. The growth of the ridge is performed in a couple of successive tidal cycles. Crucial is that the wave-energy is still low to moderate so that the swash excursion length is not too large and the velocities are not too high. The small ridge emerges every tidal cycle and the dominant processes are still related to the swash run-up and back wash processes on the crest. As soon as the ridge comes at a certain threshold height, the swash run-up will overtop the bar crest and the water will be trapped shoreward. During falling tide, this lower area will drain the water by the feeder channel and rip channel to the sea. The ridge has now a distinct slip-face and may either stabilise or migrate. Stabilisation occurs if the successive maximum high water levels are decreasing. This implies that there will not be any kind of overtopping by the swash. Swash and back wash processes are still on the seaward slope of the bar that may result in an overall increase in height. On the Dutch coast, this is the case when the tide is going from spring tide to neap tide conditions. The seaward site of the ridge may than steepen and building out in the seaward direction. This resembles the beach face development during accretive conditions (see e.g. Sonu, 1973). Migration of the bar crest in the shoreward direction occurs if the maximum high water levels are increasing. This implies that there is a permanent overtopping of the ridge at high tide. The slip-face of the bar migrates shoreward which can be seen in the sedimentary structures (see Dabrio and Polo, 1981).

Decay of intertidal ridges

The decay of an intertidal slip-face ridge is related to high-energy wave conditions offshore. As soon as low- to moderate-wave energy conditions change to high-energy wave conditions, the swash excursion lengths on the beach increase and the related velocities also increase. However, together with these changes the wave set-up increases and even a wind set-up may be added to the mean water level at high tide. This means that at the position of the crest of the ridge, the wave related processes like undertow are now the dominant processes. This will definitely cause an erosion of the ridge and a seaward directed net sediment flux (Kroon, 1994). The disappearance of a ridge may also be caused in an accretive period when the ridge merges to the beach.

The phases in ridge behaviour are observed near Egmond in case of a high-tide ridge. A low-tide ridge with the same process characteristics during low-tide, but dominant wave-related processes during high-tide differs. In case of low- to moderate-wave energy conditions, the processes during low-tide will be more intense than those at high tide (weak wave asymmetry, very weak undertow). This implies a net shoreward migration of this type of bar. In case of high wave energy conditions, the processes during both the low- and high tide will be under the influence of the wave asymmetry and the undertow. It is supposed that the seaward directed undertow transport the sediment in this area to deeper water, the subtidal zone.

7 Conclusions

The main factors that influence the intertidal bar behaviour are parameterised in the relative wave height (Figure 8). This relative wave height, expressed as the ratio between the local significant wave height and the local water depth, seems to be a promising parameter to describe the local process characteristics at distinct phases in intertidal bar development. The significant wave height is a measure of the wave action and the local water depth incorporates the water levels induced by the wind, waves and tide. Ideally, this parameter is determined close to the intertidal beach, in this study at the crest of the inner nearshore bar. The behaviour of the intertidal bars on the central part of the Dutch coast resembles the general sequence of phases. The generation occurs near the low-water line, followed by a vertical growth and shoreward migration during low-energy conditions and a stabilisation of the bar by waning mean water levels at the beach. The intertidal bars merge to the beach during low energy conditions or erode and flatten during high-energy conditions. Besides, the relaxation times in the accretionary sequence is slower than those in the erosive sequence (see also Wright and Short, 1984).

Most of the observed bar sequences over periods of months are incomplete. Quite often, the offshore wave energy conditions change before the morphology of a stage has reached a dynamic equilibrium with its local forcings. The sequence of bar behaviour is consistent along the shore, but different bar phases are sometimes simultaneously observed along the beach.

Acknowledgements

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