Rhythmic beach and nearshore topography: examples from Denmark

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Aerial photographs of nearshore bar features in Denmark have been studied and rhythmic wavelengths have been determined from a number of locations. From a knowledge of the profile characteristics, hypothetical standing edge wave periods, corresponding to the rhythmic length scales of the bars were calculated. It was found that the considerable range of rhythmic wavelengths on a given locality often may be explained as being the result of standing edge waves with a rather narrow frequency range, but of variable mode numbers. The frequency range of these edge waves often corresponds to a theoretical cut-off period given by the profile characteristics. This topographically induced cut-off may be an important parameter in the selection of frequency and structure of standing edge waves.

Keywords: *Crescentic bars, Edge waves, Frequency selection.*

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Rhythmic protuberances of the shoreline on scales of 100's of metres or somewhat less, are a common phenomenon along sandy shorelines around the world. These protuberances are called megacusps and they are often associated with crescentic nearshore bars. These bars form a mirror-image of the shoreline, with bar horns in phase with megacusps (fig. 1). Alternatively, the bar may consist of a series of regularly spaced segments attached to the shoreline and forming a greater or lesser angle with the beach. These are called transverse bars.

A collective term of these features is rhythmic beach topography. Often this type of morphology is accompanied by nearshore cell circulation, with rip currents situated in the bays between bar horns.

Rhythmic topography has been described from a variety of coastal environments, including southeast Australia (Wright et al., 1979; Short & Wright, 1984), the east coast of USA (Sonu, 1972; Sallenger et al., 1985), the Mediterranean (King & Williams, 1949), Northern Ireland (Carter & Kitcher, 1979; Shaw, 1985), Japan (Homma & Sonu, 1963) and the Gulf of St. Lawrence (Greenwood & Davidson-Arnott, 1975, 1979; Huntley, 1980). Thus rhythmic topography has primarily been studied in oceanic medium-high energy environments with large fetches.

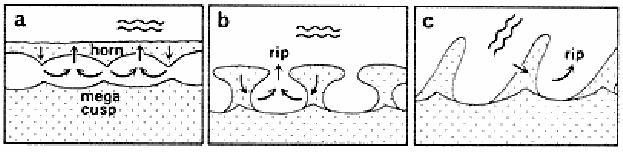

Fig. 1. Rhythmic beach topography. a) crescentic bars, b) transverse (anvil-shaped) bars, c) transverse (oblique) bars.

Factors necessary for the development seem to be

a. gentle offshore slopes,
b. availability of sand-sized sediment, and
c. small tidal range (Sonu, 1973; Greenwood & Davidson-Arnott, 1975).

The rhythmic wavelength (λ) reported in the literature ranges from about 100 to 2000 m.

The presence of rhythmic topography may exert a profound influence on coastal erosion (Bruun, 1954; Carter, 1978; Wright, 1980). Due to the nearshore cell circulation, current scour of the beach face may take place in rip bays. Also in rip bays, larger waves are allowed to propagate over the bar without breaking. Thus rip bays may be sites of severe erosion.

Greenwood & Davidson-Arnott (1975, 1979) suggested that crescentic bars were formed by the nearshore cell circulation with horns being formed by the onshore currents and bays being moulded by the rips. As the generation of nearshore cell circulation requires variations in wave height alongshore, Greenwood & Davidson-Arnott attributed these wave height variations to topographical irregularities and hypothesized a feed-back mechanism between the cell circulation and the topography. While this model may be valid under certain conditions, it does not explain the initial topographical irregularities necessary for the development of the cell circulation.

It is now generally accepted that crescentic bars and megacusps may be formed by standing edge waves (Bowen & Inman, 1971; Komar, 1983), either through the edge wave drift velocity field or by an edge wave induced cell circulation, the edge waves providing the alongshore wave height variations. According to this model, rhythmic wavelength, λ, is related to the edge wave wavelength, L_e, by

$$\lambda = L_e/2 = g/4\pi T_e^2 \sin(2n+1)\beta \qquad (1)$$

where T_e is the edge wave period, β the nearshore gradient and n is the number of offshore zero-crossings of the edge wave (the mode number).

Some field evidence for the link between standing edge waves and rhythmic topography has been provided by e.g. Wright et al. (1979), Greenwood & Bauer (1986), and Aagaard (1988a).

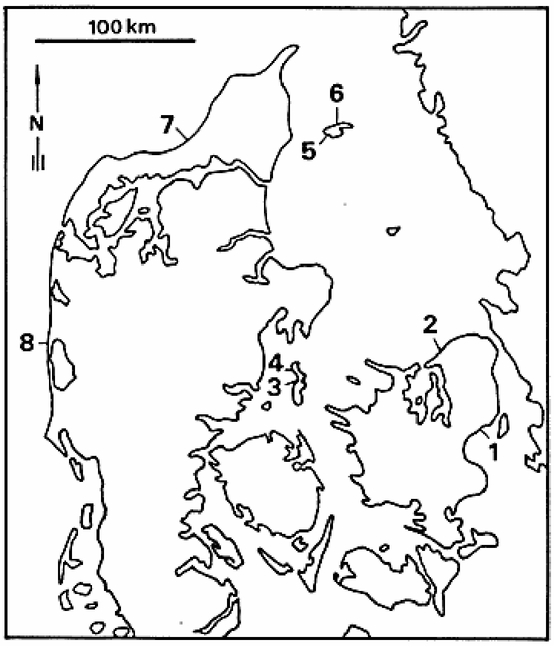

Fig. 2. Locality map. 1) Trylleskoven, 2) Stængehus, 3) Mårup Vig (south), 4) Mårup Vig (north), 5) Vesterø, 6) Hvide Bakker, 7) Blokhus, 8) Hvide Sande.

In this paper, some results from an analysis of nearshore bar morphology and dimensions will be reported. Several aerial photographs from a number of Danish localities were studied, these localities differing in exposure and offshore topography. The number of bars and their rhythmic wavelengths were registered and correlated with equation (1).

ENVIRONMENTAL SETTING AND METHODS

Localities 1 through 6 are situated along protected Danish coasts with short fetches, preventing the generation of significant swell (fig. 2). The wave energy is generally low, but these conditions may be punctuated by storms, creating relatively high wave energy events. Modal wave heights are ≤ 0.5 m with periods of 2-3 seconds while during storms, the wave height may exceed 2.5 m with periods up to 6 seconds on the more exposed localities. Tidal range is ≤ 0.4 m. While sand is not abundant, the quantities are sufficient for bars to be formed, the number of bars ranging from 2 to 5. These bars appear in ribbons; they are generally resting upon an abraded surface composed of till or clayey marine sediments.

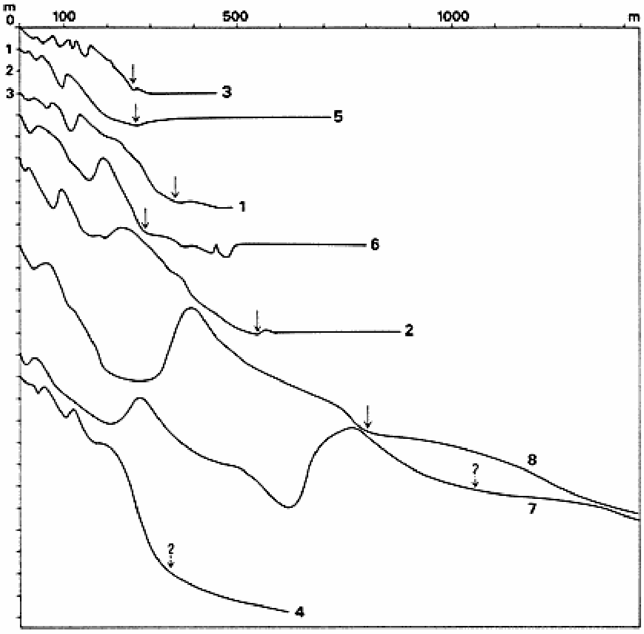

Fig. 3. Representative profiles from the studied localities. Numerals correspond to fig. 2.

Localities 7-8 are situated along the west coast of Jutland, facing the North Sea. Fetches are significantly larger than on localities 1-6, and the wave energy is higher. No long-term statistics of wave characteristics exist, but based on recordings spanning 2 years, the wave height probably exceeds 1 m for 55 % of the time and 2.5 m for 10 % of the time at Fjaltring between localities 7 and 8 (J. O. Andersen, Coastal Authority of Denmark, pers.comm.). During northwesterly or westerly storms, significant wave heights may reach 6 m with periods approaching 10 seconds. Tidal range is about 0.3 m at locality 7. Locality 8 is situated on a barrier island which has migrated across an outwash plain; sand is much more abundant on the North Sea coast than on localities 1-6. The number of bars is generally 2-3.

Aerial photographs have been taken at irregular intervals during the period 1961-1986 by the Geodetic Institute of Denmark. These photographs have been studied and the morphological characteristics of the bars and their rhythmic wavelength, if present, have been registered.

Nearshore topography and gradients have been determined using an echo fathometer. Profiles from the North Sea coast were sampled by the Coastal Authority of Denmark. Representative profiles from the individual localities are compiled in fig. 3. Nearshore gradients range from 0.006 to 0.026, the North Sea profiles being gentler (table 1). It is seen from these profiles, that a pronounced change of gradient seaward of the outer bar is common. The location of this point is indicated by arrows in fig. 3. It is assumed that the position of the slope break and the gradient between this and the shoreline is comparatively stable over time. This assumption has been supported by field studies.

RESULTS AND DISCUSSION

Figures 4-7 are examples of rhythmic bar morphology in

Fig. 4. Aerial photograph, locality 7, May 1975. Scale 1:20000. The crescentic bar 1 has a rhythmic wavelength of about 520 m. Note the rip current over the left (southern) crescent. ©Copyright Geodætisk Institut 1975 (A.497/87).

Denmark. The figures illustrate typical bar features. Rhythmicity is significant in embayments, while it is less well developed on the open North Sea coast. Bar 1 (the inner bar) exhibits the greatest relative rhythmic relief; this bar may be of either the crescentic or transverse type. Bar 2 is often weakly crescentic, while outer bars are more or less linear, apart from bars on embayed localities. Troughs between bars on localities 1-6 may be either thinly veneered with sand, or the compact bottom may be exposed.

As appears on the aerial photographs, the rhythmicity may persist under low energy conditions along the protected coasts. Instead of migrating onshore with an obliteration of the crescentic/transverse bar forms, as described by Wright et al. (1979) and Short (1979), the bars remain arrested in position and form due to long periods of very low wave energy. This phenomenon has also been described by Dolan & Dean (1985) and Aagaard (1988b).

Table 1 summarizes rhythmic wavelengths λ of bars for individual localities. $\bar{\lambda}$ increases with bar number, i.e. outer bars attain larger than inner bars do. $\bar{\lambda}$ also increases with exposure; thus $\bar{\lambda}$ is large on the North Sea coast and small on the protected localities Vesterø and Mårup Vig.

Standard deviation, σ_λ, increases with bar number, but no systematic trend in relative standard deviation ($\sigma_\lambda / \bar{\lambda}$) exists; the variation in wavelength is independent of bar number, but there seems to be a relation between relative standard deviation and location. The most protected localities (locs. 3-5) seem to display a slightly smaller $\sigma_\lambda / \bar{\lambda}$-ratio, i.e. rhythmic wavelength is less variable.

The gradient between the shoreline and the slope break in the profile is also given in table 1 as well as shore-normal fetch distance.

There seems to be no relationship between $\bar{\lambda}$ and β and whereas a connection between $\bar{\lambda}$ and fetch distance may exist. Fetch distance may be regarded as a rough measure of the size of the waves; given a fetch direction, the wave height and period will tend to be larger for greater fetch distances, other things being equal. Trylleskoven (loc. 1) is an exception from the above pattern. The reason is that the locality is exposed towards southeast, whereas storms in Denmark normally have directions between west and north.

Examining table 1 more closely, a very complex relationship may be discerned between on the one hand x_s (distance to the slope break), β and fetch distance ('wave size'), and on the other $\bar{\lambda}$ and number of bars. The -values given in table 1 conceal the fact that often there exist two different λ-ranges for a given bar on a given locality. One λ-range may be broadly identical to a λ-

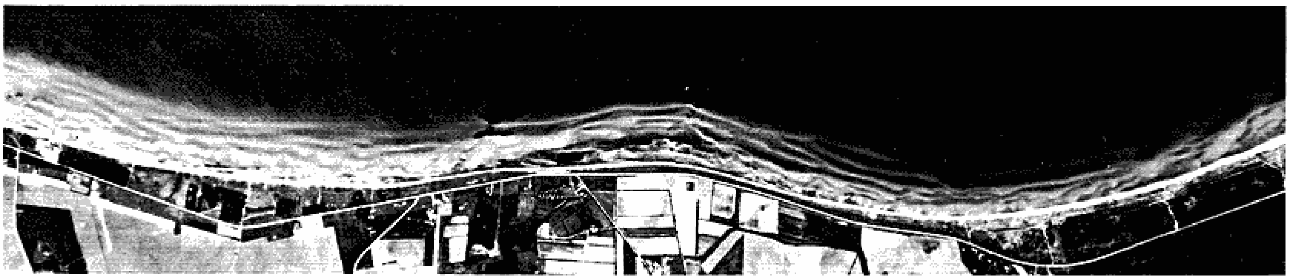

Fig. 5. Aerial photograph, localities 3 & 4, May 1978. Scale 1:25000. Locality 4 is in the upper (northern) part of the photo, while locality 3 is in the lower part. Rhythmic bars are abundant on a variety of scales. ©Copyright Geodætisk Institut 1978 (A.497/87).

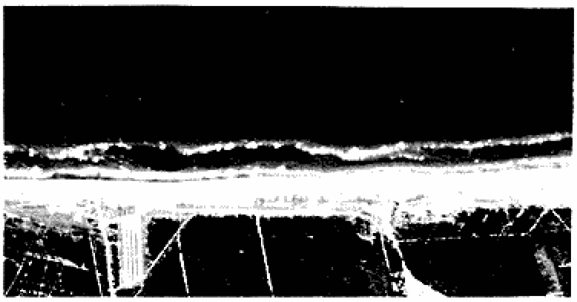

Fig. 6. Aerial photograph, locality 2, April 1984. Scale 1:25000. Bar 1 is obliquely transverse in the righthand side of the photo (east) with a wavelength of about 105 m. Bar 2 is crescentic with a wavelength of about 270 m. ©Copyright Geodætisk Institut 1984 (A.497/87).

range occurring on a more seaward positioned bar, while another λ-range may be specific for the given bar. E.g. bar 2 often has a λ-value corresponding to λ of bar 3 but in other situations, the λ-value is distinctly different from λ-values found on other bars.

This will be more closely analyzed. The analysis will focus on bar 2 as the wavelength generated in a high-energy situation is considered more interesting. The rhythmicity of bar 2 is more likely to persist under lower energy conditions than the rhythmicity of bar 1, which may reflect more moderate energy conditions. Furthermore, the rhythmic relief is more pronounced on bar 2 than on any farther seaward positioned bars.

In table 2, the λ-ranges of bar 2 are given for some of the localities. Standing edge wave periods corresponding to these ranges have been calculated from equation (1) with n tentatively given a value of 2 for the lower range and 3 for the higher range. The second bar will not be formed by edge waves having less than two zero-crossings. For n=3, the gradient between the shoreline and the slope break seaward of the outer bar has been used while for n=2, the gradient between the shoreline and the inner edge of bar 3 has been calculated.

As seen in table 2, edge wave periods seem to occupy a relatively narrow range for separate localities. An exception is Blokhus on the North Sea coast. In many cases, the large overall λ-range implied in table 1 may possibly be explained as being a result of standing edge waves with a fairly narrow range of periods, but of differing mode numbers. Note that only one λ-range exists on loc. 2 and that the relative standard deviation of λ on bar 2 is small. This may be explained as being a result of standing edge waves having similar length scales regardless of whether n=2 or n=3.

The question then arises: What is the reason for the inter-locational variance of edge wave periods? Bowen & Inman (1969) suggested that the edge wave mode number, n, depends on the width of the surf zone. They expressed this width by the non-dimensional parameter

$$X_s = \omega_e^2 x_s / g \tan \beta \qquad (2)$$

where x_s is the distance from the shoreline to the slope break and ω_e is the radian frequency of the edge waves = $2\eta / T_e$. Huntley (1976) found that the criterion for edge waves to remain trapped against the shoreline was $X_s > X_{min}$, where

Fig. 7. Oblique transverse bars and megacusps, locality 6, July 1987. Rhythmic wavelength = 130 m.

loc. no.			bar 1	bar 2	bar 3	bar 4	bar 5	no. of bars	x_s, m	β	fetch, n.m., and direction
1	Trylleskoven	$\bar{\lambda}$	76.4	158.1	265.9			4-5	370	0.014	115 (SE)
		σ_λ	26.5	55.0	80.0	-	-				
		$\sigma_\lambda/\bar{\lambda}$	.35	.35	.30						
2	Stængehus	$\bar{\lambda}$	158.6	273.7				3	520	0.014	86 (NW)
		σ_λ	82.0	25.3	-						
		$\sigma_\lambda/\bar{\lambda}$	.52	.09							
3	Mårup Vig (south)	$\bar{\lambda}$	58.6	57.6	73.0	229.7		5	260	0.011	11 (WNW)
		σ_λ	11.1	9.8	19.5	11.7	-				
		$\sigma_\lambda/\bar{\lambda}$	.19	.17	.27	.05					
4	Mårup Vig (north)	$\bar{\lambda}$	74.0	124.5	182.0			4	360	0.026	11 (W)
		σ_λ	19.1	33.6	68.6	-					
		$\sigma_\lambda/\bar{\lambda}$	.26	.27	.38						
5	Vesterø	$\bar{\lambda}$	33.2	119.0	305.4			3	250	0.013	16 (W)
		σ_λ	8.5	33.2	87.5						
		$\sigma_\lambda/\bar{\lambda}$	.26	.28	.29						
6	Hvide Bakker	$\bar{\lambda}$	126.7	229.1				2	300	0.016	74 (N)
		σ_λ	46.9	75.0							
		$\sigma_\lambda/\bar{\lambda}$	.37	.33							
7	Blokhus	$\bar{\lambda}$	347.0	667.0				3	1100/ 1700	0.006	410 (WNW)
		σ_λ	130.2	246.0	-						
		$\sigma_\lambda/\bar{\lambda}$	.38	.37							
8	Hvide Sande	$\bar{\lambda}$	977.5					2	825	0.010	350 (W)
		σ_λ	592.3	-							
		$\sigma_\lambda/\bar{\lambda}$	.61								

Table 1. λ-parameters, number of bars, shore-normal fetch and x_s and β as determined from the profiles for the studied localities. Number of observations on a given bar varies between 5 and 9. - signifies that data are scarce or missing. $\bar{\lambda}$ is mean rhythmic wavelength, σ_λ is standard deviation of $\bar{\lambda}$, and $\sigma_\lambda/\bar{\lambda}$ is relative standard deviation.

$$\chi_{min} = 3.5\, n\, (n+1) \qquad (3)$$

From equations (2) and (3), a series of cut-off periods may be expressed as

$$T_e \leq 2\pi \, {\frac{x_s}{g \tan\beta \, (\chi_{min})}}^{\frac{1}{2}} \qquad (4)$$

Huntley (1976) and Sasaki & Horikawa (1978) found that edge waves with periods corresponding to these cut-offs, i.e. edge waves covering the width of the nearshore tended to be most strongly excited, although energy seemed to be spread over several modes.

These cut-off periods have been calculated for n=3 and x_s and β as given in tables 1 and 2. Cut-off periods compare favourably with edge wave periods whose wavelength corresponds to the higher range of λ-values. One reason why the T_e-ranges in table 2 are not even narrower may be that β and x_s vary somewhat, spatially as well as temporally. The poor correlation between T_e and cut-off period at Mårup Vig (loc. 4) may be due to difficulties in determining x_s.

The results imply that profile characteristics expressed by x_s and β may be an important factor in the selection of edge wave periods and mode numbers.

But the external force initially generating the edge waves must be connected with the incident wave field, which is

loc. no.		λ-ranges, m.	n	β	T_e, sec.	cut-off period, sec.
1	Trylleskoven	100-150	n=2	0.012	47-58	
		180-250	n=3	0.014	49-57	51
2	Stængehus	250-300	n=2	0.025	51-55	
			n=3	0.014	56-62	58
4	Mårup Vig (north)	95-115	n=2	0.018	37-40	
		225-260	n=3	0.026	35-38	28
5	Vesterø	80-90	n=2	0.017	35-37	
		130-165	n=3	0.013	42-48	42
7	Blokhus	340-950	n=2	0.011	89-149	
			n=3	0.006	102-170	132/170

Table 2. λ-ranges on bar 2, mode number, appropriate gradient, calculated edge wave periods and calculated cut-off period for n = 3.

also indicated by the relationship between fetch distance and edge wave periods. A topographic cut-off can not be the sole frequency selection process, as a series of cut-off periods is predicted, each corresponding to a specific mode number. The mechanism may be an interplay between the incident wave field enabling a specific range of low frequency periods to occur, possibly through the generation of a range of wave group periods, and the profile 'selecting' a period corresponding to a topographic cut-off. Thereby n is determined; this will ultimately determine the number of bars formed and provide part of the explanation why some beaches erode more than others, as incident wave energy is dissipated over the bars. Energy dissipation due to wave breaking will increase with number of bars, other things being equal.

CONCLUSION

It has been found that the considerable range of rhythmic wavelengths on a given locality often may be explained as being the result of standing edge waves with a rather narrow frequency range.

These edge wave frequency ranges compare favourably with theoretical cut-off frequencies as calculated from the profile characteristics. The selection of edge wave frequency and structure in high-energy situations may thus be due to a complex interplay between incident wave characteristics and profile configuration. This mechanism may determine the number of bars formed and their rhythmic wavelengths and contribute to our understanding of coastal erosion problems. As waves break over bars in storm situations and energy thus is dissipated, the number of bars may be an important factor in explaining why some beaches erode more than others.

Furthermore, this model may contribute to the explanation of why some beaches display spatially variable erosion rates during storms; rips will occur at rhythmically recurrent intervals, these intervals being determined by the edge wave period and structure. Knowledge of the range of probable edge wave wavelengths during storms may be of value in coastal management and coastal erosion measures, e.g. it should be taken into consideration when dimensions and location of groynes are designed.

At present, the above considerations are hypothetical and a possible verification will depend on a large amount of field data. Investigations are proceeding along these lines.

ACKNOWLEDGMENTS

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