Observations of beach cusps

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Observations of beach cusps have been conducted under low-energy conditions on the northern coast of Zealand, Denmark. The distance between cusps showed consistently good correlation with values calculated from a hypothetical occurrence of synchronous or subharmonic edge waves. A relationship is implied between the edge wave frequency and the value of the surf scaling parameter. Supplementary observations from the southern coast of England indicate that the edge wave theory may not be adequate in explaining the distance between cusps on pocket beaches.

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Beach cusps are rhythmic morphological features located on the foreshore. They commonly appear both on sandy shorelines and on shorelines consisting of coarser sediment. The beach sediment is often sorted by grain size, with the coarser sediment in the horns. Beach cusp formation is most favourable with normally incident waves, and one of their principal features is the small variation in spacing, which can vary from few tenths of metres to more than 50 metres (Fig. 1).

The phenomenon has been widely studied, these studies having been centered around three main issues: A determination of the circulation of water and sediment in the cusps, a determination of the causative mechanism, and an explanation of the equal spacing of the cusps. A general agreement upon any of these questions has not been reached; many contradictory statements can be found in the literature.

Kuenen (1948) found that the swash is located in the troughs between cusps and the backwash along the horns, while Inman & Guza (1982) observed the opposite. Komar (1971) thought that beach cusps are depositional forms, while Smith & Dolan (1960) related their presence to erosive processes. Guza & Inman (1975) stated that their formation may be due to both.

Several hypotheses exist concerning the formation process. Among others, erosion of initial irregularities on the foreshore (Kuenen, 1948), interactions between two intersecting wave trains (Dalrymple & Lanan, 1976) and erosion of a beach ridge or a layer of seaweed (Williams, 1973). None of these hypotheses seem to be able to account for the equal spacing between cusps.

Fig. 1. Beach cusps in Liseleje June 8th 1983. Average cusp spacing: 1.5 m.

Fig. 1. Strandtakker i Liseleje 8/6-1983. Gennemsnitlig bølgelængde: 1.5 m.

Dean & Maurmeyer (1980) thought that a linear relation exists between the spacing and the swash distance, but the most widely recently proposed triggering mechanism is the presence of edge waves near the beach face.

In this paper, results of field studies conducted under low-energy conditions on the northern coast of Zealand during the summer and autumn of 1983 are reported. Additional observations took place on various coasts in southern England during the autumn of 1984. Measured cusp spacings are correlated with wavelengths of hypothetically occurring edge waves.

EDGE WAVES

Edge waves are standing or progressive waves with crests normal to the shoreline. The wavelength is measured along the coast where the amplitude varies sinusoidally. Along the shoreline, nodes where the vertical excursion of water particles is zero and the horizontal excursion is at a maximum, alternates with antinodes where the reverse is the case. The highest, respectively lowest runup is therefore located at antinodes. In the offshore direction, the edge wave amplitude is at a maximum at the shoreline, and varies sinusoidally seawards, exponentially decreasing. Thus edge waves represent a three-dimensional velocity field. The edge wave wavelength, L_e, is given by

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

(Guza & Inman, 1975), where β is the slope of the inshore or foreshore (depending upon where the edge waves occur) and n is the offshore modal number i.e. the number of zerocrossings in the offshore direction (Fig. 2). T_e is the edge wave period, and g the acceleration of gravity.

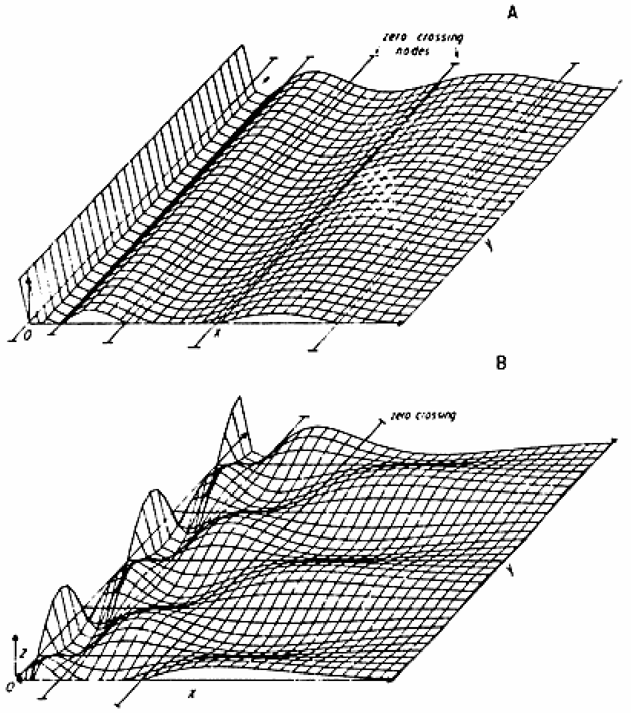


Fig. 2. Three-dimensional water level fluctuations associated with a. leaky mode standing wave, b. mode 3 edge wave (from Wright, Guza & Short, 1982).
Fig. 2. Tredimensionale vandspejlsvariationer associeret med en a. leaky mode stående bølge, b. mode 3 edge wave (efter Wright, Guza & Short, 1982).

The generation of standing edge waves seems to be related to an instability of a reflected wave, and subsequent transfer of energy from the incident waves by non-linear interactions between the incident and two edge waves of the same frequency travelling in opposite directions alongshore, a so-called resonant triad (Guza & Davis, 1974; Guza & Inman, 1975)..

The edge wave energy is trapped in the surf zone by refraction, which is one of the main differences between edge waves and standing incident waves, so-called leaky modes (Fig. 2). The refraction pattern is the reason for the three-dimensionally oscillating wavefield, and leads to the presence of a caustic in a certain distance from the shoreline (Hoogstraaten, 1972), which prevents loss of energy.

The surf zone must be of a certain width for the edge waves to remain trapped. This width may be expressed by the non-dimensional parameter

$$X_s = w_e^2\, x_s / g \tan \beta$$

(Bowen & Inman, 1969), where $w_e = 2\pi/T_e$ and x_s is the distance from the beach face to the breakpoint (Wright et. al, 1979). The criterion is $X_s > X_{min}$, where

$$X_{min} = 3.5\ n\ (n + 1)$$

(Huntley, 1976).

Two main types of edge waves occur:

1. Surf beat resonance with periods of 30-300 s, covering the width of the inshore. Under certain conditions their frequencies may be topographically restricted, the edge wave being trapped between the foreshore and a longshore bar (Wright et. al, 1982).

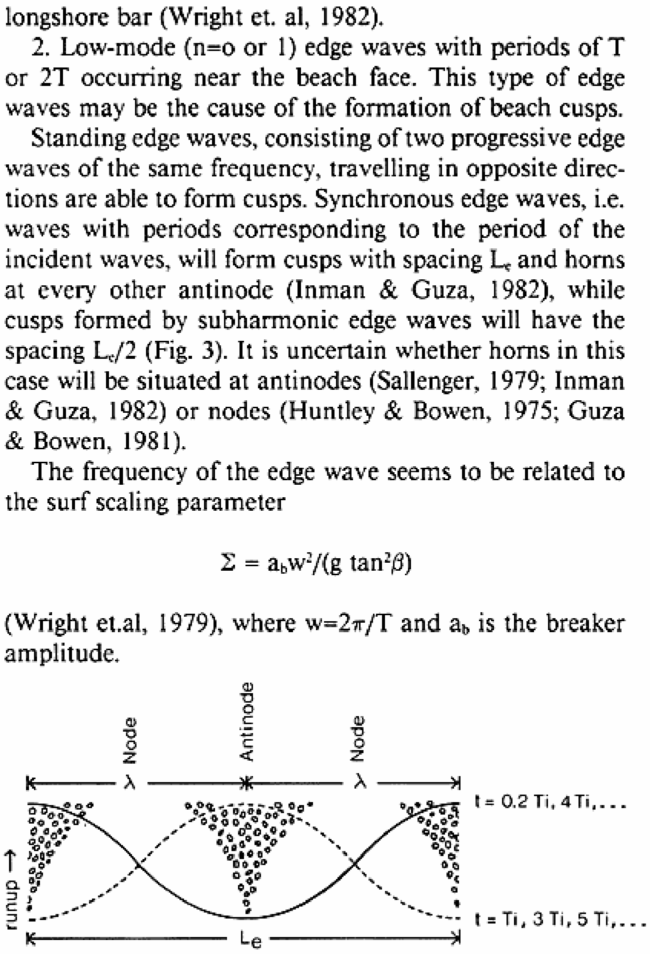
2. Low-mode (n=o or 1) edge waves with periods of T or 2T occurring near the beach face. This type of edge waves may be the cause of the formation of beach cusps.

Standing edge waves, consisting of two progressive edge waves of the same frequency, travelling in opposite directions are able to form cusps. Synchronous edge waves, i.e. waves with periods corresponding to the period of the incident waves, will form cusps with spacing L_e and horns at every other antinode (Inman & Guza, 1982), while cusps formed by subharmonic edge waves will have the spacing $L_e/2$ (Fig. 3). It is uncertain whether horns in this case will be situated at antinodes (Sallenger, 1979; Inman & Guza, 1982) or nodes (Huntley & Bowen, 1975; Guza & Bowen, 1981).

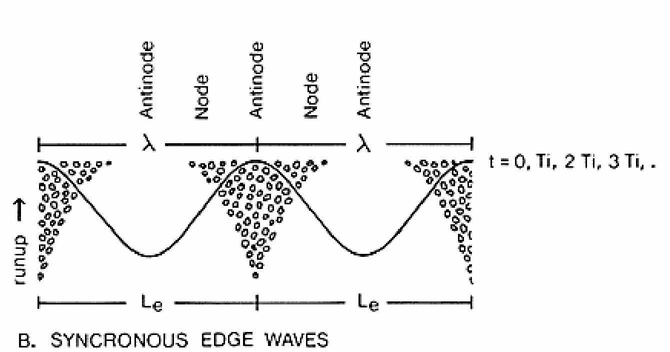
The frequency of the edge wave seems to be related to the surf scaling parameter

$$\Sigma = a_b w^2 / (g \tan^2 \beta)$$

(Wright et.al, 1979), where $w = 2\pi/T$ and a_b is the breaker amplitude.



A. SUBHARMONIC EDGE WAVES



B. SYNCRONOUS EDGE WAVES

Fig. 3. Run-up variations at the beach face caused by a. subharmonic edge waves, b. synchronous edge waves. The position of cusp horns are indicated. Adapted from Inman & Guza (1982).
Fig. 3. Opskylsvariationer på forstranden forårsaget af a. subharmoniske edge waves, b. synkrone edge waves. Strandtakkernes placering er angivet. Efter Inman & Guza (1982).

date	Σ	measured average λ	λ calculated from			
			synchronous edge waves		subharmonic edge waves	
			n=0	n=1	n=0	n=1
8/6-83	1.7	1.5 m	1.7 m	5.1 m	3.5 m	
11/9-83	2.9	2.5 m	2.9 m		5.8 m	
16/9-83	8.5	4.0 m	0.7 m	2.1 m	1.4 m	4.2 m
16/9-83	1.8	1.5 m	0.8 m	2.5 m	1.6 m	

Table 1. Comparison between measured and calculated cusp spacings, Liseleje.

The incident waves will be reflected if $\Sigma < 2.5$ and breakers will be surging. Dissipation of energy increases with Σ, and the breakers will be spilling for $\Sigma > 20$. For $2.5 < \Sigma < 20$ plunging will prevail (Wright, Guza & Short, 1982).

When dissipation is increased, the generation of high-frequency edge waves is suppressed due to friction and energy loss (Guza & Bowen, 1976) and edge waves of lower frequencies are preferentially generated. The formation of beach cusps is therefore restricted to situations when Σ at the beach face (Σ_b) is low, i.e. when the foreshore is sufficiently reflective for synchronous or subharmonic edge waves to be generated. Low wave height, long-period swell and coarse sediment will therefore each favour the formation of cusps.

RESULTS

The field study took place at Liseleje on the northern coast of Zealand. The environment is dominated by wind waves.

The composition of the sediments in the area is inhomogenous. The greater part consists of medium-sized sand, while shingle and cobbles are concentrated in smaller pavements. Cusp spacings were registrered, profiles were measured with level and rod and period and breaker height of the incident waves were determined. The results are presented in Table 1 below. λ is the average spacing between cusps.

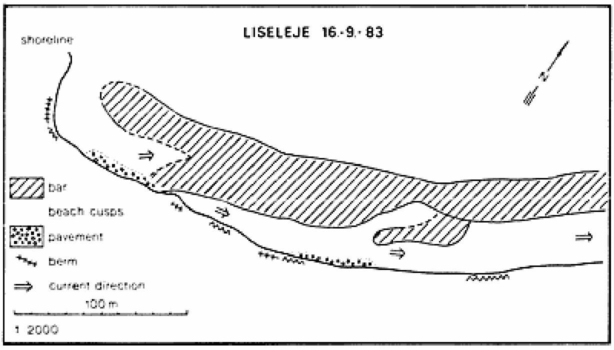


Fig. 4. Morphological map, Liseleje September 16th 1983. Cusps are present both in the western and eastern »basin«.

Fig. 4. Morfologisk kort, Liseleje 16/9-1983. Strandtakkerne optræder både i det vestlige og i det østlige bassin.

locality	T	β	measured average λ	λ calculated from			
				synchronous edge waves		subharmonic edge waves	
				n=0	n=1	n=0	n=1
1.	4.6 s	12°	2.3 m	6.9 m	19.4 m	13.7 m	
2.	4.8 s	8°	5.0 m	5.1 m	14.6 m	10.0 m	
3.	6.0 s	16½°	4.9 m	16.0 m	47.9 m	31.9 m	
4.	6.5 s	11°	8.5 m	12.6 m	36.0 m	25.2 m	
5.	6.0 s	16°	3.7 m	15.5 m	46.5 m	31.0 m	

Localities are:
1. Lulworth Cove 17/9-84
2. Weymouth 19/9-84
3. Durdle Door 20/9-84
4. Lulworth Cove 20/9-84
5. Watcombe Cove 22/9-84

Table 2. Comparison between measured and calculated cusp spacings, Southern England.

On June 8th and September 11th, the breaker height and hence Σ were very small, which leads to a high degree of reflection. The breakers were surging with H_b=0.1 m. Under these conditions, synchronous or subharmonic edge waves are preferentially generated, and the very narrow surf zone leads to the conclusion that the modal number probably would be n=o. In both cases, spacings calculated from the occurrence of a synchronous mode o edge wave showed the best correlation with the measured spacings.

On September 16th cusps were present in two areas, separated by an oblique shore-attached bar (Fig. 4). The average spacings were 4.0 m in the eastern, and 1.5 m in the western area, respectively. In the western part breakers were surging (H_b= 0.05 m) and the theoretical spacing calculated from a subharmonic mode o edge wave shows the best correlation with the actual spacing. This is somewhat surprising. Due to the very small braker height, synchronous edge waves would have been more likely to occur. In the eastern part H_b was o.2 m. Breakers were plunging near the beach face, which makes it reasonable to assume that possible edge waves would have a higher mode number, as the surf zone was broader, than in the western part. Under these conditions, edge wave frequency would be expected to be lower than that of the incident waves. Distances calculated from a mode 1 subharmonic edge wave fit the actually measured spacings.

Cusps characteristically appeared where the foreshore slope was the steepest.

Further observations took place on various beaches in southern England during September 1984. T, β and λ were measured, but H_b was not, so Σ has not been calculated (Table 2).

Lulworth Cove (Fig. 5) and Durdle Door are both situated east of Weymouth, while Watcombe Cove is at the north of Torquay. Lulworth Cove, Durdle Door and Watcombe Cove are all pocket beaches with a high proportion of the sediment in the foreshore consisting of shingle and gravel. The shoreline in Weymouth is straight on the stretch where cusps appeared (Fig. 6). In Weymouth,

Fig. 5. Beach cusps in Lulworth Cove September 20th 1984. Average spacing: 8.5 m.
Fig. 5. Strandtakker i Lulworth Cove 20/9-1984. Gennemsnitlig bølgelængde: 8,5 m.

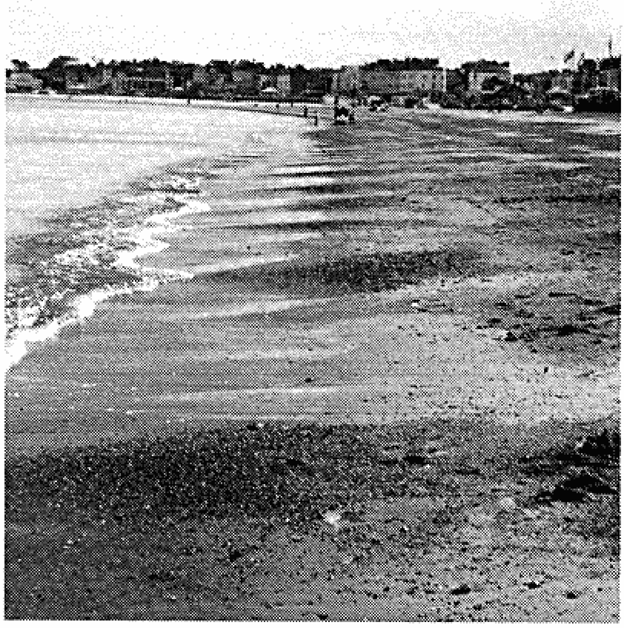


Fig. 6. Beach cusps in Weymouth September 19th 1984. Average spacing: 5.0 m. Note the sorting of the sediment.
Fig. 6. Strandtakker ved Weymouth 19/9-1984. Gennemsnitlig bølgelængde: 5,0 m. Bemærk materialesorteringen.

breakers were very low and surging, which makes it reasonable to assume that a relation could exist between cusp spacing and a synchronous mode o edge wave.

In the pocket beaches, distances between cusps consistently were too small to be explained by the edge wave theory.

DISCUSSION AND CONCLUSIONS

The spacings between cusps in Liseleje consistently showed good correlation with spacings calculated by the edge wave theory, although measured λ invariably was a bit smaller than calculated λ. Discrepancies may arise from the difficulty in assigning a monochromatic wave period (which is required in eq.1) in the field. As cusp distances in eq.1 depends on T^2, small uncertainties in the determination of T will have a great influence on the calculation of L_e. Another source of error may be variation of the foreshore slope.

Furthermore, a dimensional connection was found between cusp spacing and the degree of reflection, expressed by Σ_b. When Σ_b increases, T_e and therefore L_e will increase, albeit discontinually (Wright et.al, 1979), which is consistent with these observations. For very low values of Σ_b and surging breakers, the cusp spacing agreed with synchronous edge waves; with increasing Σ_b and plunging breakers, subharmonic edge waves showed the best fit. Results in the western area on September 16th deviate from this pattern, but conditions in the lee of the breakwater were probably influenced by conditions on other parts of the shoreline.

When Σ_b theoretically was too high for the generation of shoreline-restricted, high-frequency edge waves (i.e. $\Sigma > 20$ and spilling breakers), no cusps were found.

The observations from England indicate that a genetic difference may exist between cusps formed on straight coastlines and in bays. Reasons for this can only be surmised, but it may be due to diffraction around headlands in pocket beaches. It appears from Fig. 7 that two wavetrains with different angles of incidence exist in Lulworth Cove, which leads to the conclusion, that the mechanism proposed by Dalrymple & Lanan (1976) in this case may have formed the cusps.

The obtained results show that edge waves may have been the reason for the occurrence of cusps in Liseleje and in Weymouth. In order to get a more certain verification of a causality, it would have been necessary to measure energy spectra of variations in water level, η, and current velocities to investigate whether a correspondance exists between measured spectral peaks, and the edge wave period calculated from λ. Spectral peaks will be caused by standing edge waves if a phase difference of $\pi/2$ exists between η and offshore current, u, and if u and longshore current, v, correspondingly are in phase. Further evidence will be an offshore decrease in the spectral peak. The presence of synchronous edge waves cannot be detected in the spectra, as it is extremely difficult to separate these from progressive incident waves.

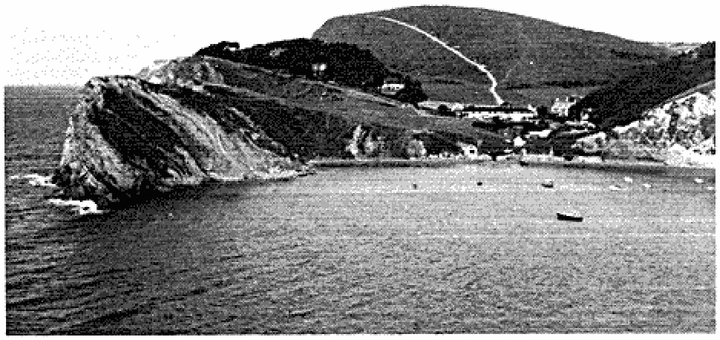


Fig. 7. Diffraction in Lulworth Cove. The inclined strata in the background are late-Jurassic limestone from the Purbeck-formation.
Fig. 7. Diffraktion i Lulworth Cove. De stejltstillede lag i baggrunden er sen-jurassiske kalksten fra Purbeckformationen.

On the other hand, edge wave theory may not be adequate in explaining the distance between cusps on beaches where diffraction has a profound influence on the wave pattern.

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Resumé

Dannelsen af strandtakker har hyppigt i litteraturen været tilskrevet tilstedeværelsen af low mode stående synkrone eller subharmoniske edge waves.

Afstande mellem strandtakker optrædende i Liseleje på nordkysten af Sjælland er blevet målt og sammenlignet med afstande, som ville have resulteret hvis takkerne var dannet af edge waves. I alle tilfældene udviste de målte afstande god korrelation med den mest sandsynligt forekommende edge wave. Med strandbrænding, meget lav brændingshøjde og små værdier af surf scaling parameteren Σ var korrelationen bedst med en synkron mode o edge wave, mens afstandene, med en bredere overføringszone, styrtbrænding og en større værdi af Σ, var i overensstemmelse med en subharmonisk mode 1 edge wave. Når Σ teoretisk var for stor til at højfrekvente edge waves kunne eksistere fandtes heller ingen strandtakker.

Observationer fra Weymouth, England passer i dette mønster, mens målinger fra forskellige små bugter på sydkysten af England viste, at her var afstandene mellem takkerne konsekvent for små til, at takkernes tilstedeværelse kunne forklares af edge wave teorien. Om årsagerne hertil kan der kun gisnes, men måske skal forklaringen søges i, at de indfaldende bølger bliver diffrakteret omkring forbjerge, hvorved der dannes to bølgetog med forskellige indfaldsretninger.

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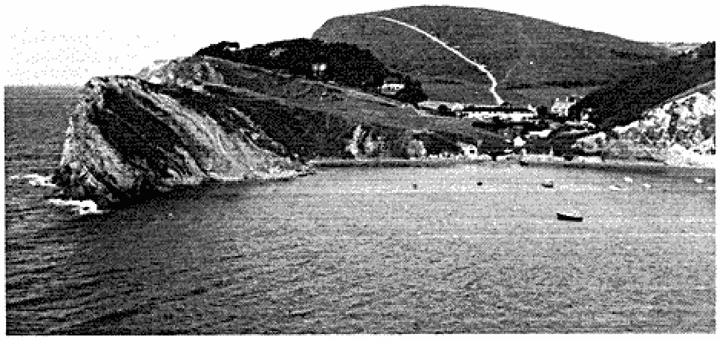

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