

## RHYTHMIC BEACH CUSP FORMATION: A CONCEPTUAL SYNTHESIS\*

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### ABSTRACT

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Observations of a sandy beach at Santa Barbara, California, during February 1980 documented the sequence of beach cusp formation, replacement by a second set of rhythmic cusps obliterating the first set, and finally complete planation of all rhythmic cusps during a major storm. Although neither cusp-building event was observed during its initiation, the wave and tide conditions during formation were well documented by in-situ instrumentation. Based on these field observations and those by other investigators, a coherent conceptual theory of beach cusp formation is proposed, including formative, maintenance and destructive phases. This theory proposes rhythmic cusp formation during relative stillstands of sea level of sufficient duration to permit initial perturbation of beach geometry; regularly spaced cusps acquire their initial spacing from subharmonic edge waves (such that spacing derives from the incident wave period); growth of the initial perturbation continues until cusps reach a limiting value, not necessarily with continuation of edge wave motion; the cusp spacing persists until a change in wave conditions either destroys the cusps, or establishes a radically different spacing; and finally, that large storms will destroy the rhythmic cusp field, leaving either a planar beach or a beach with arrhythmic cusp-like features.

### INTRODUCTION

Rhythmic shoreline features have long been of interest to coastal geologists, geographers, and engineers. From the first descriptions of beach cusps (Palmer, 1834), there have been apparently contradictory observations and theories of rhythmic morphological development, particularly for beach cusps which are observed only after formation, and which are relatively ephemeral. The practical importance of these features is multi-fold, with perhaps one of the most exciting aspects being their possible response to trapped wave motions which dominate surf zone processes under certain conditions of beach slope and wave form. Since direct observation of these trapped waves is difficult, the indirect expressions perhaps left by them take on added importance.

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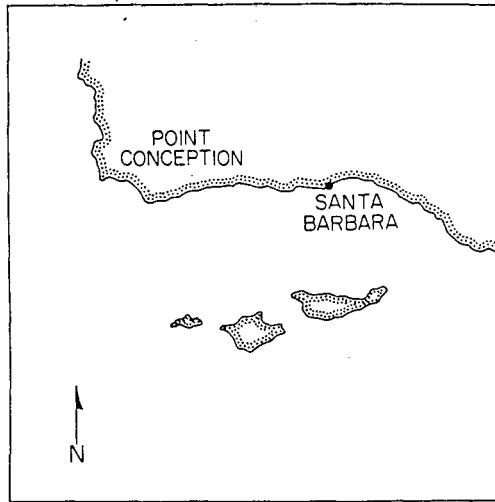


Fig. 1. Location of Santa Barbara, California, relative to Point Conception headland and the offshore islands.

The authors had an opportunity to observe the formation of a series of beach cusps during a field experiment in January and February of 1980 (Fig. 1). These rhythmic beach cusps were generated on a field of pre-existing cusps, which were subsequently obliterated. The new set of cusps were then destroyed during a major storm, with a 50–100 year recurrence interval (Fig. 2). These observations, combined with accurate measurements of the forcing conditions, provoked us to synthesize ideas of rhythmic beach cusp generation using other investigators' observations as well.

The literature on beachface cusp formation is vast, and a substantial lack of consensus still exists on the causative mechanisms and the limiting conditions for existence. The phenomenon considered here excludes mobile bed forms that involve longshore transport, such as the sand waves described in Homma and Sonu (1963), Sonu (1968, 1973), and Schwartz (1972). It also excludes giant cusps of the type described in Komar (1971), as well as cusp-like forms caused by storm erosion on an accreted beach (Evans, 1938, type 1; Williams, 1973, storm cusps). It is restricted to rhythmic features that form at the upper portion of the swash zone with wavelengths of tens of centimeters to tens of meters.

A more thorough review of the literature (see Guza and Inman, 1975; or Sallenger, 1979) points out an obvious conflict between and among observationalists and theoreticians. Some of the more pertinent differences are discussed here. (We do not present an exhaustive review.)

Shepard (1935) observes that gravel cusps are more persistent during intervals of neap tides, implying that they are destroyed by large tide ranges. Schupp (1953) discusses accretional cobble beach cusps in southern California, and verifies the tendency for gravel cusps to form during neap tides, and to disintegrate during spring tides. Otvos (1964) contends that

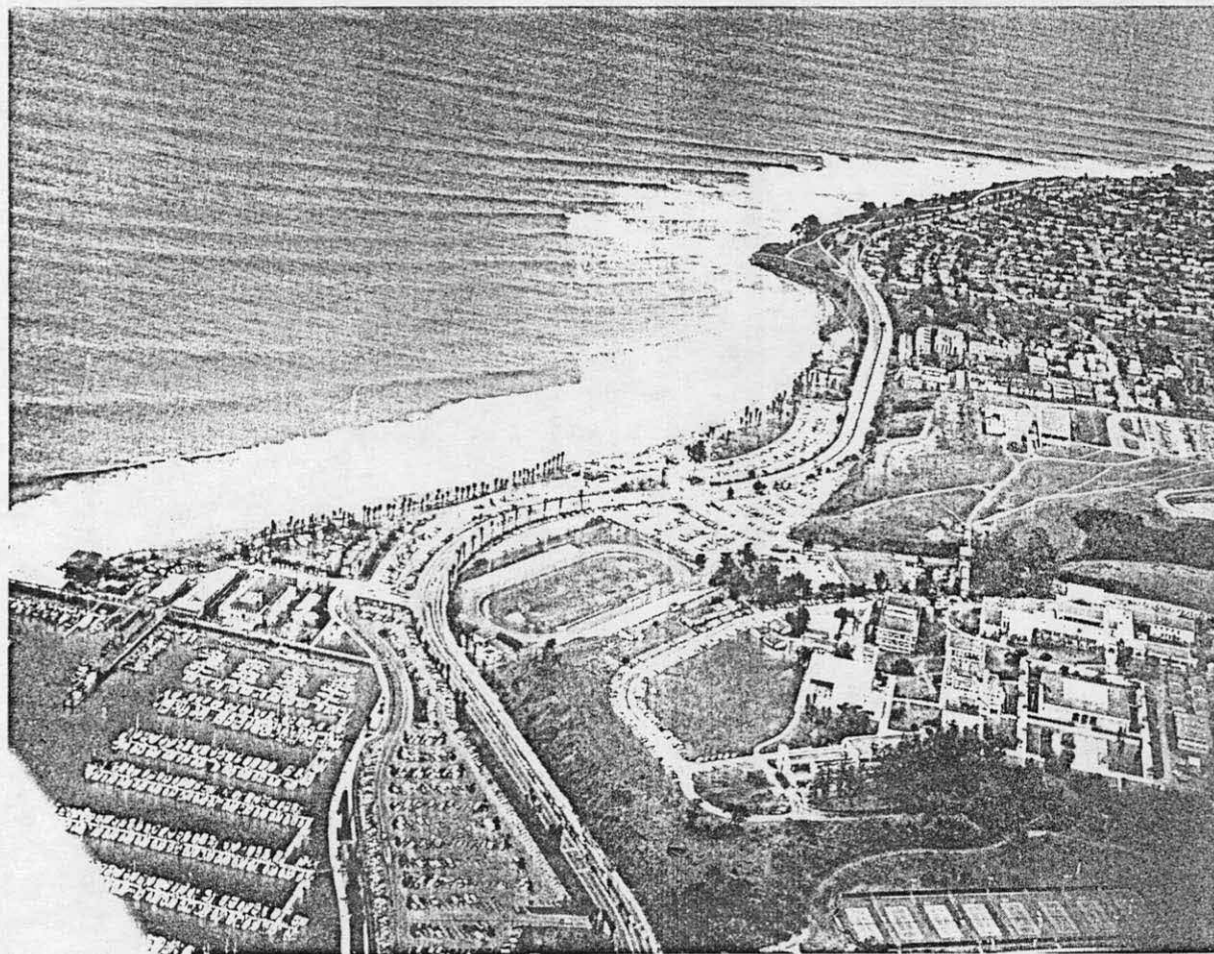


Fig.2. Leadbetter Beach, Santa Barbara, California, during the storm of 16–21 February, 1980. The NSTS experiment area was seaward of the athletic field in the left foreground (photograph by M.P. Clark).

tide stages are not important in forming fine sand cusps and pebbly-coarse sand cusps. At Otvos' field site (Westbrook, Connecticut), spring/neap tidal range ratio is 1.35, with a spring range of 1.4 m. Longuet-Higgins and Parkin (1962; hereafter referred to as LHP) observe two sets of cusps, one at the high-tide swash and one at the low-tide swash, even with a tide range of 4 m. This discrepancy can be alleviated on the following basis. Shepard's observations showed that when incident waves were not so large as to destroy the cusps, cusps formed most readily and survived to the greatest extent when the tides were both diurnal and in the neap phase. A careful reading of Otvos shows that he was referring only to cusps formed in coarse sand and pebbles when he dismissed the tide stages. Later in his paper he indicates that cusps formed on the fine sand beaches in his study area only when the high-tide level remained nearly stationary for 30–45 min. LHP investigated very steep shingle beaches with grain sizes in the pebble to cobble range. At these sites, cusps formed in a matter of minutes at each stillstand and were eliminated practically without trace by the following tide cycle. Tide tables for the April 1956 LHP observations show two highs only about 10 cm different in elevation and about two hours apart during the obvious daylight cusp-building event. The long high-tide duration is a regional anomaly. If the time required for the cusp to grow to its limit (or equilibrium) steepness is less than the stillstand interval, then tide ranges are unlikely to influence the formation of the cusps. Conversely, if the growth time is large compared to a stillstand, the smearing effect of changing sea level could inhibit cusp formation. Clearly, neap tides will provide more slowly changing sea levels at the high than will springs, and diurnal tides more than semi-diurnal. Large tidal ranges will tend to smear or destroy beach cusps formed during low-water stillstands.

Many other investigators have observed multiple co-existing sets of beach cusps, all at different levels. Russell and McIntire (1965) observed two and three sets of cusps on various occasions, at distinct levels of the beach. Williams (1973) observed three rows of cusps on Hong Kong beaches, with the highest level coinciding with the higher high-water position, the middle set coinciding with the high-tide position, and the bottom level marking the lower low-water position. Stillstand of sea level was mentioned as a factor favoring cusp formation.

A host of investigators (including Galvin, 1965; Bowen and Inman, 1969; Sallenger, 1979; Guza and Bowen, 1981; and Inman and Guza, 1982) provide theoretical and observational evidence for edge waves as the triggering mechanism for cusps, providing the template for cusp spacing and location.

The longshore wavelength,  $L_e$ , and period,  $T_e$ , of edge waves on a plane beach are related (Eckart, 1951):

$$L_e = \frac{g}{2\pi} T_e^2 (2n + 1) \tan \beta \quad (1)$$

where  $g$  is the acceleration of gravity,  $n$  is the mode number, and  $\beta$  is the beach slope. The most easily excited edge wave, the lowest mode ( $n = 0$ )

is a subharmonic with a period twice that of the incident wave period (Guza and Inman, 1975). Cusp wavelength is hypothesized to be equal to one-half the wavelength of a subharmonic edge wave ( $\lambda_c = L_c/2$ ). Thus, the wavelength of the beach cusp can be expressed as (Inman and Guza, 1982):

$$\lambda_c = \frac{L_e}{2} = \frac{g}{\pi} T_i^2 \tan \beta \quad (2)$$

for the subharmonic case. Ball (1967) derives an analytic solution for edge waves on non-planar beaches, while Munk et al. (1964) and Holman and Bowen (1979) provide numerical schemes for finding the edge wave dispersion relation [analogous to eqn. (1)] for arbitrary cross-shore beach configuration. Kuenen (1948), Otvos (1964) and Schwartz (1972), among others, present arguments, unsupported by data, that higher waves result in larger cusp spacing. Dalrymple and Lanan (1976) postulate that this large wave/large cusp spacing may be related to the observation that the higher the wave, the longer its wavelength. LHP and Dean and Maurmeyer (1981; hereafter referred to as DM) show a correlation between swash excursion and cusp spacing. Many other theories of formation exist, emphasizing the influence of topography on cusp formation (Otvos, 1964; Williams, 1973; Dubois, 1978; Sallenger, 1979); and the role of incident waves and swash (Longuet-Higgins and Parkin, 1962; Dalrymple and Lanan, 1976). In particular, observations show a relationship between accretionary cycles of beaches and formation of beach cusps, particularly in association with a beach ridge on berm (Evans, 1938; Otvos, 1964; Williams, 1973; Dubois, 1978; Sallenger, 1979). Except for possibly the edge wave theory, none of these theories adequately explains the rhythmic nature of beach cusps. Since few investigators observed cusp formation while documenting wave conditions, the linkage between cusps and incident waves is weak.

The LHP study attempted to discern correlations between swash spacing and the predicted wavelengths of edge waves at one of their sites (Tide Mill) but found none. The assumption was that each observation constituted a unique cusp-building event. In the light of observations by Evans (1938) and Sallenger (1979) that subtle perturbations of the beachface can serve as a template for cusp spacing, the insignificant-seeming remnants of the previous cycles may have set the cusp wavelength for later episodes. This argument is supported by LHP data from 23 and 24 April when cusp spacing remained identical for two days, even though swash excursion varied. A similar event occurred at the second LHP site (Chesil Bank). On 21, 22 and 23 June, cusp spacing varied over only 15% of the mean length while swash excursion varied by a factor of almost 3.

The DM study involved a single observation of a cusp-building event. Wave period was estimated from visual observations of wave breaking and therefore position of breaking (few studies have measured pertinent wave parameters with accurate wave gages). Subharmonic edgewave prediction of cusp spacing obtained with this period estimate disagreed with the measured mean spacing by 30%. As pointed out in Inman and Guza (1982; hereafter

called IG), an error of only 15% in estimating the period would result in a match between the wavelengths. Further, DM assumed that the wave period observed after the cusps were well-formed represented the candidate period for testing edge wave generation mechanisms. Evans (1938) observed waves acting on cusps when those waves were "...totally unrelated to their process of formation. This is very likely to be misleading to the investigator who starts with a finished series of cusps and who may be led to a deductive explanation because of the great difficulty of making direct observations during their growth".

The single observation of the DM study does not appear to rule out edge waves as a source mechanism. The LHP results cast serious doubts that the waves observed were responsible for cusp spacing. But the cusps were presumably initiated by some set of waves. During the Chesil Bank experiment, observed wave periods ranged from 5 to 7 s. Beach slopes ranged from 0.09 to 0.2. Cusp spacings were 3.7–10 m. For the five observations in June, predicted minimum cusp spacing from an edge wave source is at least twice too large, based on wave periods existing at the time of cusp measurement. Noting that all of these observations were made at high tide, tide tables for those dates show that the daylight highs occurred between 1:30 and 5:45 p.m., appropriate for high-frequency waves locally generated by landward winds over the Atlantic. A reduction of the period by only 30% during the early morning (sea-breeze dominated) high would allow any of these events to serve as the template of cusp building for all following observations. During the four observations in July, edge wave theory provides reasonable estimates (within 15–30%) of the cusp spacing using wave periods measured at the time of the observation.

The DM study also develops a simple model of water particle excursion over the cusp geometry which predicts cusp spacing as a function of swash period, and therefore the maximum swash excursion. This relationship agrees reasonably with their field observations and with those of LHP. DM claim that this correlation between swash amplitude and cusp spacing supports this mechanism as the one governing cusp formation. They offer no justification for this beyond rejecting edge waves as the probable cause; nor do they treat the inconsistency in their predictive relationship which would yield a near zero cusp spacing at initiation from a plane beach when cusp relief is small. The DM mechanism envisions accretion on the horns and erosion in the bays and a tendency to reinforce existing cusp topography. This is in good agreement with the reasoning of IG. However, an initial rhythmic disturbance is required by IG to predispose the beach face towards cusp formation. IG favors edge waves as this mechanism, but allows for other causes. The DM theory does not discuss how cusp growth is limited. IG presents a relationship for a limiting height to length ratio for cusps which agrees reasonably well with observed data.

Observations of Evans (1945), Short (1979) and Sallenger (1979) present convincing evidence that, under conditions of an initially planar beach and low, surging breakers, the rhythmical variation in swash set up by subhar-

monic edge waves is a likely mechanism for establishing regular cusp spacing. Any positive reinforcement theory on a planar beach with random perturbations cannot lead to regular spacing without prolonged competition between neighboring sites. It does not seem possible that such a non-deterministic scheme could produce Evans' observation of a perfect set of cusps generated in less than two minutes from a planar beach. The only mechanism yet proposed for initiating cusps that will rapidly produce regular spacing from a planar beach is edge wave theory.

However, the observed correlation between swash excursion and cusp spacing must be explained. LHP merely notes the correlation and DM assumes from the observation that swash determines cusp spacing. It seems equally likely that the inverse is true, or that the correlation is fortuitous. Neither LHP nor DM cite any direct evidence showing a change in cusp spacing that occurs in response to a change in swash height. The LHP data, however, include two series in which cusp spacing remains fixed although swash height varies significantly.

As previously noted, there are a number of anecdotal observations that big waves result in large cusp spacing. Given that cusps form only when incident waves are less than a critical value of steepness, large cusp-building waves necessarily imply long periods. Long-period waves drive, in turn, long-period edge waves and large cusp spacings.

One observed attribute of cusp stability that has produced no disagreement is the tendency for storm waves to destroy cusps and plane off the beach. No theories have been advanced for this effect. In light of the previous arguments, it may be instructive to extend them to the case of instability under storm waves. Assume a set of regularly spaced cusps, built and maintained by low swell. Now introduce storm waves and consider the effects on the swash. As shown by Guza and Thornton (1982), there will be a substantial increase in energy at frequencies of order 1/10 the breaker frequency, which will grow with incident wave height. This mismatch in dominant swash period and excursion (with infragravity wave dominance) can be expected to erase the cusp field rapidly. As noted by LHP, waves whose height is too great for the vertical dimensions of the cusps tend to sweep over the cusp promontories and destroy them.

#### METHODOLOGY

In January and February of 1980, a major field experiment of the Near-shore Sediment Transport Study (NSTS) was undertaken at Leadbetter Beach in Santa Barbara, California (Gable, 1981). Leadbetter Beach is a 3 km long sandy beach protected from open ocean waves by the headland of Point Conception and a string of offshore islands and reefs (Figs. 1 and 2), resulting in a low-to-moderate wave climate throughout most of each year. Median grain size in Leadbetter Beach is 0.23 mm. As a result of the large grain size and the wave climate, the foreshore is relatively steep ( $\tan \beta = 0.38$ ).

Gable (1981) provides an exhaustive description of the experiment site, the instrumentation and the method other investigators may use to obtain raw data from the Leadbetter Beach experiment. In addition to the traditional concern for changes to the characteristic nearshore beach-profile shape, this investigation was directed towards study of its longshore variability. Therefore, profile measurements were made both parallel and perpendicular to the shoreline. Subaerial beach and foreshore profiles, in both directions, were measured with conventional rod-and-level techniques to a depth of approximately  $-1$  m relative to mean sea level. Five primary ranges established in the cross-shore direction (Fig.3) were sampled from one to three times per day during the interval from 27 January to 25 February, 1980. Immediately prior to the experiment (22 January, 1980) and at the close (25 February, 1983), these five ranges were extended seaward to 15 m depth using a small boat equipped with a sonic depthfinder and an electronic navigation system. The ranges parallel to shore were measured during most, but not all, of the experiment period. The area of investigation centered on a section of beach 2000 m wide extending seaward approximately 600 m (Fig.3).

Measurements generally followed the methodology described in Nordstrom and Inman (1975). Details of the NSTS coordinate system and a schedule of the measurements are contained in Gable (1981). In order to

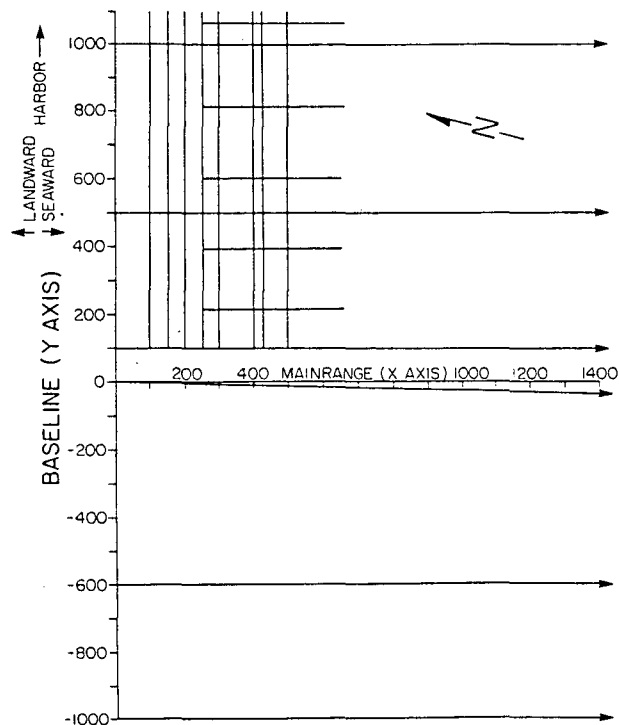


Fig.3. Location of beach survey lines at Santa Barbara.



assure the highest possible quality, data from the rod-and-level surveys were entered into a microcomputer in the field immediately following each set of surveys. The resulting profiles were plotted and compared to earlier results to highlight anomalous points, allowing for prompt resurveys of any doubtful points. The profiles were stored on magnetic tape cassettes which were later archived onto a 9-track tape.

In addition to these data, beach and offshore surveys at approximately six-week intervals covered the entire length of Leadbetter Beach at coarser spacing. These were obtained by Robert G. Dean over a period of about 18 months as part of an NSTS experiment to measure longshore transport using the spit at the eastern end of the beach as a sand trap (Dean et al., 1983). Two of these broad area surveys, from 21 January and 25 February 1980, bracketed the month-long field experiment and are included to provide an overall perspective of beach changes. Surveying methodology for these profiles was essentially identical to that described above. Waves were measured by two directional pressure gage arrays (Gable, 1981). Directional wave spectra were measured four times daily.

## RESULTS

Early in the morning of 2 February, 1980, a series of well-defined depositional beachface sand cusps was observed. Measurements showed the cusp spacing varied by a factor of 3 (approximately 16–48 m). On the previous day, 1 February, the cusp spacing had been approximately 19 m, and much more regular. The general appearance of the 2 February beach was of superposition of 40 m long cusps on the pre-existing 19-m cusp field. Subsequently, the cusp spacing changed radically over a few-hour interval. By 5 February the cusp spacing had become regular, averaging about 40 m. Maximum horn-to-bay elevation difference was about 75 cm. These cusps persisted through February 11, but with diminishing relief. On the 12th they were diminished further and by the 13th they had been planed away except for some remnants on the berm above the swash zone.

Cusps were surveyed with transects parallel and perpendicular to the shoreline each day during the cusp event except for 3, 5 and 10 February. In the period from 13 to 25 February no new cusps were formed. Initial and final stages of the cusps along a 100 m length of beach are represented by profiles from 4 and 13 February, respectively (Fig.4). On 4 February, the third day of the cusp event, the cusps were well-defined and exhibit the characteristic deltas at the bases of the valleys, as described in Inman and Guza (1982). By 11 February, the deltas were no longer discernible. Relief of the cusp horns was diminished, but their basic location remained stationary. Two days later, on 13 February, all cusp features were absent from the active beachface.

Wave height (Fig.5) in February fluctuated from a mean of about 0.50 m up to 12 February, to a maximum of about 2 m (with a daily average of 1.5 m). Mean peak period (daily averaged values of modal wave period)

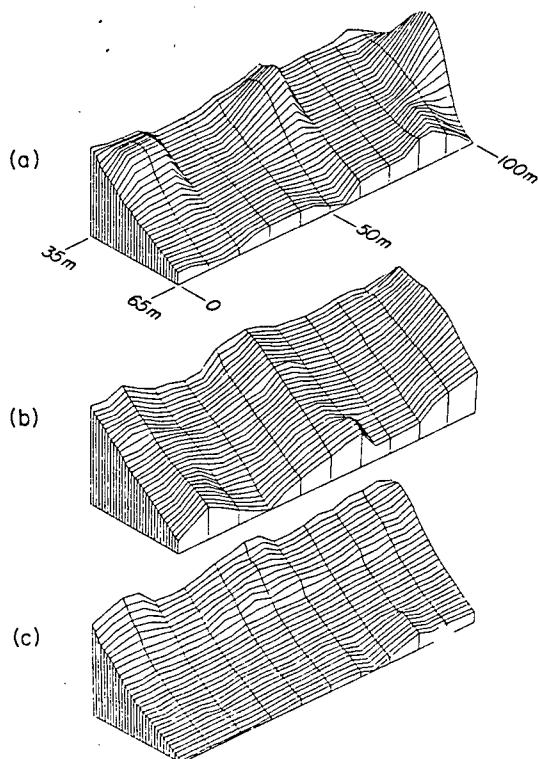


Fig.4. Beach cusps at Santa Barbara (a) 4 February, 1980; (b) 11 February; (c) 13 February.

varied from approximately 5 to 18 s. Spring tides occurred in early February (2 m range) and 14–17 February (2.3 m range).

#### DISCUSSION

Based on previous observations by other investigators and our own measurements at Santa Barbara, a strong case is made for a coherent theory of cusp formation and maintenance that is consistent with the published literature. The elements of this theory, which is in substantial agreement with IG, are:

(1) Cusps are formed during relative stillstand of sea level which last long enough to allow the cusp geometry to reach a stable height. Because of subsequent erosion during flood tide, the high-tide cusps tend to persist longer than low-tide cusps. Similarly, spring high-tide cusps persist longer than neap high-tide cusps.

(2) Regularly spaced cusps acquire their initial spacing from rhythmic perturbations of the swash produced by subharmonic edge waves driven by low steepness waves, most likely exhibiting plunging or surging breaking behavior. Thus, cusp spacing is determined by the incident wave period.

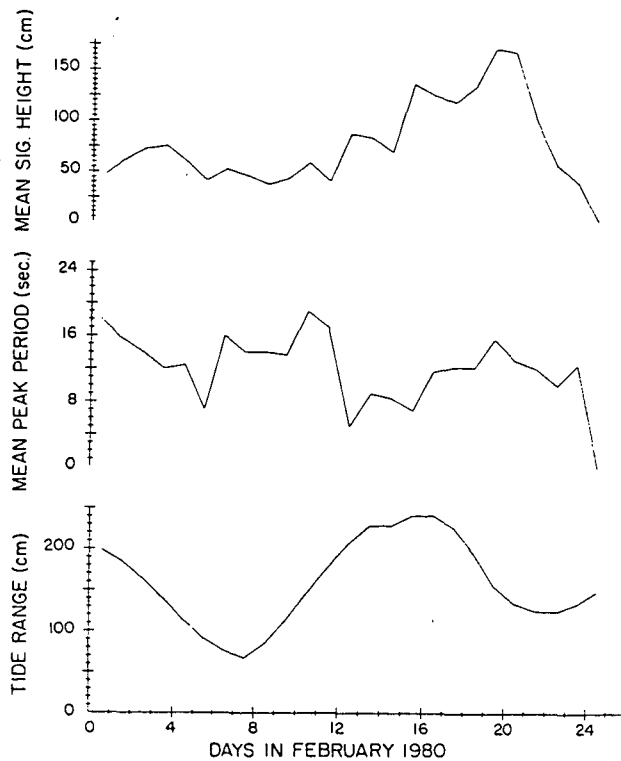


Fig. 5. Wave and tide parameters, Santa Barbara NSTS Experiment.

Beach ridges or berms are not necessary for cusp initiation, although such beach morphologies will increase the tendency towards formation of depositional cusps.

(3) The initial perturbation grows under the constructive mechanism described in IG and DM until its elevation reaches a limiting value. This limiting value may not agree with the IG theory. Subsequent beach accretion or longshore transport may fill in cusp bays (or swales), reducing cusp steepness.

(4) Once a cusp spacing has been incised into the beach, it will dominate the mean spacing until a wave event occurs that establishes a radically different spacing, until storm waves destroy the existing system entirely, or until beach cusps are completely filled in by cross-shore or longshore sand transport (e.g., Wright et al., 1982). Cusp spacing does not casually adjust to existing wave conditions.

(5) Storm waves will destroy a cusp field, leaving the beach planar. Only arrhythmic cusp-like erosional morphologies may result from storm waves.

Since the cusp event in early February at Santa Barbara contains creation, maintenance and destruction elements, it serves as a test for the coherent theory described above.

First, the generation process is examined. Stable depositional cusps with a wavelength of approximately 40 m were formed on a beach with a mean

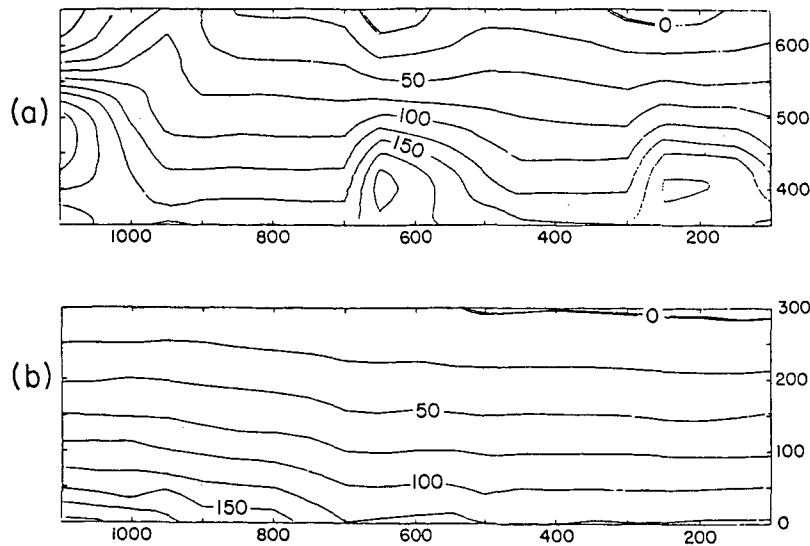


Fig. 6. (a) Beachface contours, 4 February, 1980, at Leadbetter Beach. Longshore and cross-shore distances are in decimeters. Elevations contours are in centimeters relative to MSL with an interval of 25 cm. (b) Comparable depth regime on 21 February after the peak of the storm.

slope of approximately 0.05 (Fig. 6a), replacing remnant cusps with 19 m spacing. Incident wave period during the early morning of 2 February (when cusps were formed) was about 16 s. Using eqn. (2) to predict cusp spacing for subharmonic edge waves yields a wavelength of 39.9 m, as compared to the eventual steady state value of 40 m. Since wave height increased between the first and the second day of the month and the tide range was decreasing, one might anticipate that the more closely spaced cusps be superseded by a new regime. The higher waves would tend to destabilize the existing cusps. The lower high tide mark would allow edge waves to incise a new template just below the old cusp location. The supplanting of the 20 m cusps by 40 m cusps, a rather chaotic process, appeared to proceed from east to west along the study area. Edge waves, formed by low steepness plunging breakers on 2 February, appear to be the generating mechanism. Since the cusps were initiated at night, we did not observe the actual initiation process.

The cusps appeared to have reached equilibrium by 4 February. Therefore, their height on this date can be examined with the limit steepness relationship suggested in IG. The Inman-Guza theory predicts that the cusp height would fall between 26 and 48 cm for a cusp spacing of 40 m and a slope of 0.05. The observed value of about 75 cm is significantly higher than this prediction, and is much steeper than any of the examples presented in the IG data set.

The next element of the coherent theory that can be explored using the Santa Barbara cusp event is the maintenance of cusp geometry through varying incident wave conditions. During the period from 2 to 11 February,

mean peak wave period varied between 7 and 19 s. Mean daily significant wave height ranged between 35 to 75 cm. Tide range varied from 0.7 to 1.75 m. During 6 February, a short episode of locally generated storm waves developed, as evidenced by a drop in the period of peak energy from 12 to 7 s (Fig.5). This caused a slight erosional trend on the beachface, and reduced the elevation of the cusps by less than 20 cm. The storm was of insufficient intensity or duration to completely eliminate the cusps, so they survived through 11 February without significant planform changes.

On 13 February, a second local storm developed with a mean period of about 5 s. The difference between this event and the one on 6 February is the greater high-frequency energy. The significant wave height is considerably greater on the 13th, while the swell contribution to this height is negligible. This type of incident spectrum (as shown in Guza and Thornton, 1982) produces an increase in both the amplitude and the period of the swash. The storm of the 13th, as predicted in the present theory, destroyed the cusps. It should also be noted that the tide range was increasing rapidly at this time and had reached the approximate level that existed when the cusps were formed. It does not seem possible to separate the contribution of the increased tide range from that of the storm waves because of the temporal coincidence. Local superelevation due to wind stress may also increase the maximum water level, thereby increasing the tendency for cusp obliteration.

Following the storm of 13 February, a series of storms of increasing intensity persisted until the 23rd, extensively eroding the beach. During the final days of the experiment, 24 and 25 February, the wave and tide range conditions appeared to be similar to those earlier in the month which had supported cusps, but no cusp formation was observed.

The theory of cusp formation does not require cusps to be cut into a beach ridge or berm, as suggested by Evans (1938), Otvos (1964), Williams (1973), Dubois (1978), and Sallenger (1979). Prior to the 2 February 1980 cusp event, there was no such beach ridge or berm present where the cusps were formed, even though the beach was in an accretionary state or stable state when the cusps were formed. In accord with IG, our theory does not require beach ridges or berms for cusp formation, although they may increase the tendency for cusp formation. Ponding of water behind the ridge may accelerate bay (swale) erosion. Any material available for transport may increase the tendency of the beach to respond to subharmonic waves. For instance, Schupp (1953), in a rare instance where cusp formation was actually observed (though waves were not accurately measured), documented pebbles and cobbles forming beach cusps on a sand beach. Because of their hydrodynamic response to waves, these coarser particles are often the easiest for waves to move; thus they might be the first to respond to subtle edge wave perturbations.

Lack of available sediment for beach cusp formation explains the lack of cusps from 24–25 February. Since storm waves moved most beach sand far offshore, and since beach cusps during their initial stages are depositional,

there was inadequate excess sediment available in the swash zone to form beach cusps.

## CONCLUSIONS

Observations of beach cusps at Santa Barbara, California, combined with work by others, permit a synthesis of beach cusp formation in nearly complete agreement with measurements. The elements of this theory are:

(1) Cusps are formed during relative stillstands of sea level which last long enough to allow the cusp geometry to reach a stable height. Because of subsequent erosion during flood tide, the high-tide cusps tend to persist longer than low-tide cusps. Similarly, spring high-tide cusps persist longer than neap high-tide cusps.

(2) Regularly spaced cusps acquire their initial spacing from rhythmic perturbations of the swash produced by subharmonic edge waves driven by low-steepness waves, most likely exhibiting plunging or surging breaking behavior. Thus, cusp spacing is determined by the incident wave period. Beach ridges or berms are not necessary for cusp initiation, although such beach morphologies will increase the tendency towards formation of depositional cusps.

(3) The initial perturbation grows under the constructive mechanism described in IG and DM until its elevation reaches a limiting value. This limiting value may not agree with the IG theory. Subsequent beach accretion or longshore transport may fill in cusp bays (or swales), reducing cusp steepness.

(4) Once a cusp spacing has been incised into the beach, it will dominate the mean spacing until a wave event occurs that establishes a radically different spacing until storm waves destroy the existing system entirely, or until beach cusps are completely filled in by cross-shore or longshore sand transport (e.g. Wright et al., 1982).

(5) Storm waves will destroy a cusp field, leaving the beach planar. Only arrhythmic cusp-like erosional morphologies may result from storm waves.

The theory matches observations of cusp formation, maintenance, and destruction on sand beaches. It agrees with many observations of gravel and cobble cusps, though not all. Still unexplained are some of Otvos' (1964) observations that tide stage is unimportant in formation of coarse sand cobble cusps (even though a stillstand was deemed necessary for formation of fine sand cusps). Special beach morphology such as berms or ridges which can pond water in the backshore are not necessary for cusp formation, although such ponding may accelerate definition of bays (swales). The only morphology required for cusp formation appears to be a slope which will support edge wave generation (generally large slopes leading to non-dissipative surf zones).

Although descriptive, the present synthesis provides a framework for further observation of rhythmic beach features. New studies can address specific elements of the present theory, to test their universality more rigorously. The Santa Barbara observations disagree with the Inman-Guza

(1982) limiting steepness theory, since observed cusp steepness exceeded that predicted by theory by a factor of two. More work is necessary to define limiting cusp steepness, which depends on swash processes as proposed by Inman and Guza (1982) and Dean and Maurmeyer (1981), amongst others. Cusp spacing is consistent with subharmonic edge wave forcing, although direct measurement of such forcing coincident with cusp generation is lacking. We await a complete model of wave/sediment interaction in the surf zone to clarify condition for edge wave generation and cusp formation maintenance and destruction.

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