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Beach cusp morphology on sand and mixed sand and gravel beaches, South Island, New Zealand

T.J. Nolan [a,*], R.M. Kirk [a], J. Shulmeister [b]

[a] *Department of Geography, University of Canterbury, Private Bag 4800, Christchurch, New Zealand*
[b] *Geology Department, Victoria University, Wellington, New Zealand*

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Abstract

The morphology of beach cusps on a number of beaches around the South Island, New Zealand is described. Cusp dimensions such as spacing, elevation, amplitude, depth, and spacing variance are interrelated. Cusp dimensions co-vary in regular fashion under different process conditions, such that the cusp form displays a high degree of regularity. Beach cusp amplitude is an exception to this regularity, that appears to be controlled by factors such as grain size and beach slope. Analysis of cusp spacing and elevation dimensions on mixed sand and gravel beaches reveal that cusps having particular spacings form at distinct elevations on the beachface, with the largest spacings occurring at the highest levels on the beachface. The relationship between cusp elevation and spacing provides a technique through which beach cusp spacing can be used to infer mean sea-level. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: beach cusp; morphology; morphimetry; mixed sand and gravel beach

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1. Introduction

Beach cusps are crescentic rhythmic topographic features located on the foreshore of beaches in a wide range of coastal environments. They exhibit a quasi-uniform wavelength along the shore, consisting of approximately equally spaced mounds or ridges of beach material (horns) which are separated by smoothly curved depressions (bays). The horns, generally located at right angles to the shoreline, are spaced at more or less regular intervals along the shore (Gary et al., 1974). The longshore spacings between horns generally fall in the range 20 to 60 m (Komar, 1983), but spacings can range from as little as 2 cm (Komar, 1983) to over 100 m (Mii, 1958).

Beach cusps occur in a large range of sediment sizes, from fine sand to boulders (Mii, 1958; Russell and McIntire, 1965). They generally display a size sorting of material between the horns and the bays, with the horns being made up of coarser sediment than the bays (Longuet-Higgins and Parkin, 1962: Komar, 1983).

Since first described in the literature by Palmer (1834), beach cusps have proved difficult to explain because they are relatively uniform features which have no readily apparent formation mechanism to account for their symmetrical appearance. Numerous hypotheses have been proposed in an attempt to account for cusp formation and their regular spac-

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* Corresponding author. Fax: +64 (3) 364-2907; E-mail: tim@geog.canterbury.ac.nz

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ing (for reviews, see Sallenger, 1979; Komar, 1983; Werner and Fink, 1993; Holland and Holman, 1996). Many of these models are contradictory, and this lack of consensus is taken here to indicate that more than one cusp formation mechanism could exist, and that beach cusps could display 'equifinality' (Antia, 1987).

While most beach cusp research has been directed toward the divination of a formation mechanism, other important aspects of cusps have largely been overlooked. Cusp morphometry is one of these aspects. Morphometry is the study of the shape of landforms, so beach cusp morphometry examines how the shape of cusps varies spatially and temporally. The aim of this paper is to describe relationships that exist between the different beach cusp dimensions.

Previous investigations of beach cusps have noted the existence of more than one set of cusps on a beach (see for example, Carter, 1988; Miller et al., 1989; Sherman et al., 1993). Typically, sets are situated at different levels on the beachface (Fig. 1), with an increase in age and spatial dimensions with elevation on the beachface. The highest cusp set exhibits the greatest spacing, with a progressive decrease in the spacing of the cusp sets with decreasing elevation on the beachface. The largest cusps are related to higher energy events that are temporally infrequent (i.e. storms). Although many researchers have observed this (for example, Mii, 1958; King, 1965; Williams, 1973), no research has been reported on the morphometry of this phenomenon.

2. The study sites

In order to determine the nature of the relationships between different beach cusp dimensions, a range of beach types was chosen to gain representative samples of different cusp forms. Of particular importance was the need to gauge beach cusp activity on mixed sand and gravel beaches, because most previous cusp observations have been carried out on either sandy (for example, Dean and Maurmeyer,

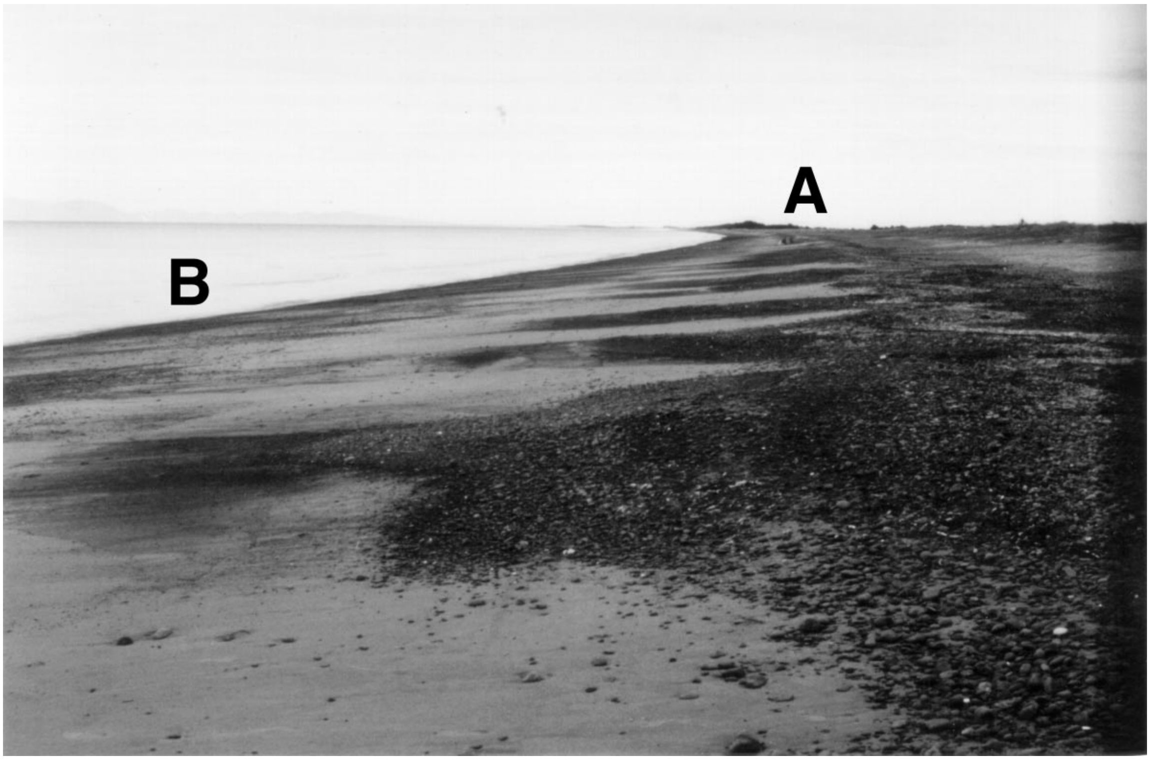

Fig. 1. Photograph of two sets of cusps at Amberley Beach. The higher set (set 1) is indicated by *A*, and the lower set (set 2) by *B*.

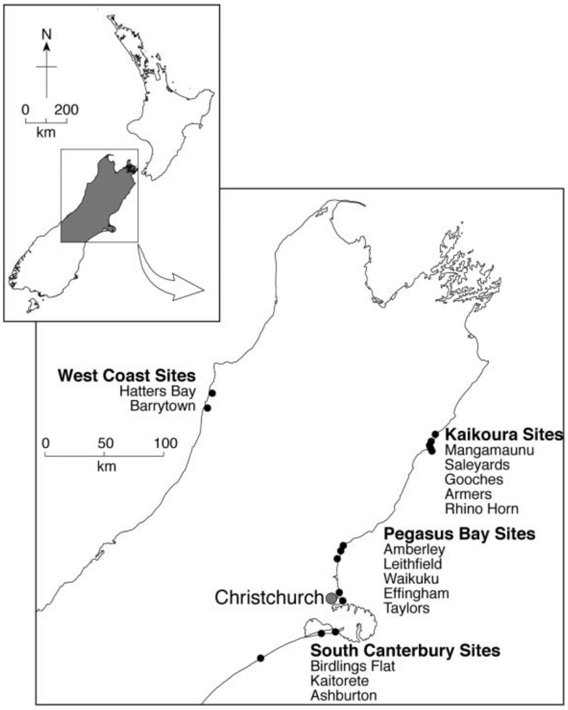

Fig. 2. Location map of the study sites.

1980; Inman and Guza, 1982; Takeda and Sunamura, 1983) or gravel beaches (for example, Longuet-Higgins and Parkin, 1962; Sherman et al., 1993). For this reason, two mixed sand and gravel beaches, Leithfield and Amberley, in Canterbury, South Island, New Zealand, were chosen to be the focii of cusp observations (Fig. 2).

Zenkovich (1967) noted that mixed sand and gravel beaches are comparatively rare on the world scale and, because they are often inaccessible, the processes that operate on them have not received much attention. In New Zealand, however, mixed sand and gravel beaches are relatively common and well studied, particularly on the east coast of the South Island (Kirk, 1980). Mixed sand and gravel beaches present the maximum range of grain sizes to wave action. They are also dynamically complex and morphologically distinctive. Because they contain elements of both pure sand and pure gravel beaches, their response is distinct from either of the two pure types of beaches (Zenkovich, 1967).

New Zealand mixed sand and gravel beaches exhibit distinct profile morphologies as well as distinct sediment characteristics. They are typically narrow in profile (100 to 200 m), steep (5° to 12°), and broadly convex in shape (Kirk, 1980). A high proportion of longshore transport occurs in the swash zone by beach drifting, and because of this the lower part of the foreshore can therefore be regarded as the 'engine room' of mixed sand and gravel beaches (Kirk, 1980).

In addition to being distinctive in profile, mixed sand and gravel beaches are unique in the alongshore configuration they present to incoming waves. Beach cusps are a major component of this, causing radical changes in morphology and sediment characteristics over relatively short alongshore distances (<100 m). This can be seen in Fig. 3, which shows the spatial alternation in runup that is influenced by the presence of cusps.

Observations of beach cusps were carried out over a 13 month period from June 1992 until July 1993. Table 1 is a summary of the individual site characteristics of the study beaches. The beaches are subject to semidiurnal tides and are mesotidal with a maximum range of 2.6 m (Kirk, 1980). Average breaker heights are 1 m to 2 m, while storm waves can be from 3 m to 6 m (Kirk, 1980). The dominant wave period is 10–15 s, with a secondary locally generated component of 6–8 s. Cusp activity was documented on a range of beach types, with the cusps composed of a large range of sediment sizes from fine sand (2.00 ϕ) to gravel (-5.00 ϕ). The two beaches concentrated on in this study, Leithfield and Amberley, are mixed sand and gravel beaches the sedimentary characteristics of which are summarised in Table 1, and in more detail in Table 3.

3. Methods

Beach cusps have a number of measurable dimensions, such as spacings, depths, elevations, and amplitudes. Regularities in these dimensions and relationships between dimensions are of particular interest. For measurement consistency, definitions of the variables are shown in Fig. 4.

Cusp spacing (C_s or λ_c) is defined as the horizontal distance alongshore between the points of highest relief on two cusp horns. Cusp amplitude (C_a or η_c) is defined as the maximum height difference (relief) of the cusp horn and the cusp bay (Guza and Bowen,

Fig. 3. Photograph of spatial alternation in runup that is caused by the presence of beach cusps.

Table 1
Summary of individual site characteristics of the study beaches

Location	Type	Beach width (m)	Aspect	Slope (°)	Cusp levels	Sediment size (M_z ϕ)[a]
Kaitorete	mixed	100	S	5–8	3–4	−1.72
Leithfield	mixed	100	E–SE	3.5–6	3–4	−0.75
Amberley	mixed	60	E–SE	4.5–8	3–4	−1.85
Gooches	mixed	60	NE	4	3	−0.50
Saleyards	mixed	100	E	6	3	−1.55
Mangamaunu	mixed	40	SE	6.5	4	−2.49
Barrytown	mixed	75	NW	10	4	−3.35
Birdlings	gravel	30	S–SW	8–24	1	−4.90
Rhino	gravel	20	SW	7	3	−1.92
Ashburton	gravel	50	SE	4.5	1	−3.40
Taylors	sand	50	NE	5	1	1.49
Effingham	sand	100	NE	3	1	2.22
Waikuku	sand	100	E–SE	3	2	2.44
Armers	sand	100	NE	5.8	2	2.75
Hatters	sand	50	NW	8	1	0.82

[a] Mean grain sizes in phi (ϕ) units.

1981). This measurement is taken from the highest point on the cusp horn (in a line parallel to the shoreline) to the lowest point in the cusp bay (Fig. 4). Cusp depth (C_d) is defined as the distance from the maximum high point on the cusp horn to the limit of swash excursion in the rear of the bay (Fig. 4).

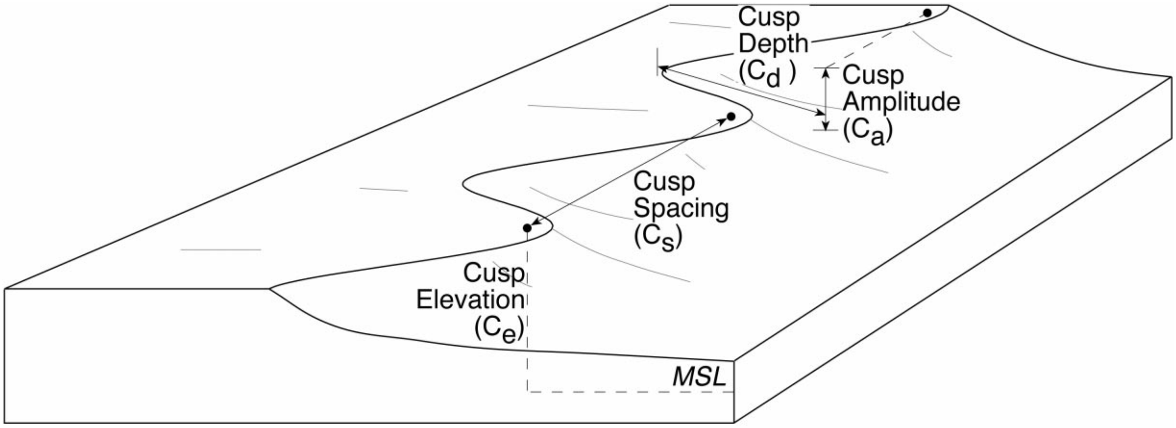

Fig. 4. Definition of beach cusp parameters measured.

Unfortunately cusp depth was not measured for every cusp set for two reasons. The depth was found to be difficult to determine during high tide, when the seaward most cusp relief was under water. The second problem was reworking of the higher cusp levels' relief by subsequent (post-depositional) wave and wind action, unrelated to the initial cusp-forming episode. Cusp elevation (C_e) is defined as the highest point on the cusp horn above a datum (in this case the regional datum, Mean Sea-Level (MSL)). Cusp spacing and depth were determined with a tape measure, while amplitude and elevation and beach slope were obtained from beach profile surveys.

4. Cusp dimensions

Over the study period 630 measurements on individual cusps were collected, amounting to a total of 68 cusp sets. Mean cusp spacings ranged from 2.95 to 87.43 m with the coefficient of variation (cusp spacing standard deviation divided by mean cusp spacing) ranging from 0.044 to 0.422. Cusp elevations ranged from 6.66 m above MSL to −0.71 m below MSL, while cusp amplitudes ranged from 0.05 m to 2.7 m. Cusp depths ranged from 2.5 to 41.2 m. A summary of the statistics collected on each cusp set over the study period is given in Table 2.

Linear regression analysis was carried out on beach cusp dimensions to determine what relationships existed between them. This regression analysis calculated the best fit line using the least squares method and the Pearson's product moment correlation coefficient (r). The coefficient of variance (r^2) and the significance level of the relationship were also calculated.

4.1. Beach cusp morphology

Beach cusp shape is generally described as rhythmic accumulations of sediment on the foreshore (Komar, 1983). These accumulations are predominantly crescentic shaped, and point seaward (Sallenger, 1979), although they can take the form of gravel ridges perpendicular to the shoreline (Otvos, 1964; McManus, 1973).

These two cusp morphologies were found on South Island beaches, the more common crescentic shape (90% of observations) and gravel ridges on the beachface (10% of observations). The gravel ridges took two forms, one separated by sand embayments and the other by gravel embayments.

Komar (1983) states that one of the principal features of beach cusps is sorting of the sediment according to grain size, with cusp horns generally displaying coarser sediments than those in the bay. South Island beach cusps frequently fit the size sorting pattern, with horn sediments coarser than bay sediments (Table 3). The exception to this pattern was sand beaches, which displayed little or no grain size differentiation (Table 3). This observation agrees with those of Shepard (1963) and Otvos (1964), who also observed little sediment size differentiation between horn and bay on sand beaches.

Table 2
Summary of beach cusp statistics for the study period

Beach	Cusp level [a]	Mean elevation (C_{e}) [b] (m)	Mean spacing (C_{s}) (m)	C.V. [c]	Ampl. (C_{a}) (m)	No. data (n)
Amberley						
12/01/93	set 2	2.55	16.71	0.208	0.95	9
	set 3	0.55	12.2	0.422	0.35	6
03/02/93	set 1	3.65	38.65	0.115	0.55	8
	set 2	2.65	27.33	0.127	0.80	25
25/02/93	set 2	2.95	29.24	0.136	0.70	15
	set 3	1.15	29.77	0.110	0.30	8
26/03/93	set 1	3.35	32.03	0.155	0.20	10
	set 2	2.15	24.25	0.163	0.40	6
	set 3	1.25	18.18	0.158	0.70	15
02/04/93	set 2	2.55	26.36	0.106	0.80	9
27/04/93	set 2	2.64	29.86	0.197	0.50	8
21/05/93	set 1	3.95	33.61	0.063	0.30	8
	set 2	2.65	30.55	0.095	0.60	10
31/05/93	set 2	3.20	31.95	0.107	0.40	6
	set 3	2.10	20.45	0.366	0.70	12
14/06/93	set 2	2.85	19.85	0.127	0.80	6
Leithfield						
04/07/92	set 1	4.50	45.50	0.081	0.60	5
	set 3	2.50	21.68	0.192	0.30	39
19/11/92	set 1	3.00	35.75	0.127	0.72	8
	set 3	2.84	26.51	0.181	0.95	10
25/11/92	set 1	2.89	37.82	0.169	0.75	8
16/12/92	set 1	2.14	18.49	0.145	0.40	14
12/01/93	set 3	1.19	14.95	0.146	0.45	5
03/02/93	set 1	2.79	23.32	0.149	0.75	27
04/02/93	set 2	1.94	23.68	0.054	0.55	8
25/02/93	set 1	2.69	33.67	0.268	0.75	13
02/03/93	set 3	1.29	26.60	0.173	0.20	8
09/03/93	set 1	2.39	30.50	0.299	0.40	6
18/03/93	set 2	2.49	35.81	0.140	0.45	6
	set 3	1.79	19.42	0.352	0.20	15
26/03/93	set 1	4.19	46.65	0.150	0.80	8
	set 2	2.79	32.28	0.117	0.80	8
	set 3	−0.51	21.90	0.300	0.20	7
	set 4	−0.71	9.44	0.375	0.30	20
02/04/93	set 3	2.49	34.20	0.180	1.10	16
18/04/93	set 2	3.26	35.58	0.129	0.50	6
	set 3	2.13	26.46	0.192	0.40	14
24/06/93	set 2	3.49	33.05	0.136	0.80	6
Waikuku						
30/05/93	set 1	1.66	47.60	0.047	0.40	5
	set 2	0.66	2.95	0.319	0.05	8
Armers						
17/02/93	set 1	0.89	14.18	0.190	0.30	5
	set 2	1.29	11.4	0.083	0.20	5
Effingham						
09/04/93	set	2.54	18.48	0.280	0.11	6
15/05/93	set	3.30	33.71	0.255	0.10	7
Taylors						
15/04/93	set	0.96	21.70	0.347	0.20	7

Table 2 (continued)

Beach	Cusp level [a]	Mean elevation (C_e) [b] (m)	Mean spacing (C_s) (m)	C.V. [c]	Ampl. (C_a) (m)	No. data (n)
Rhino						
18/02/93	set 4	2.07	4.58	0.181	0.30	6
Gooches						
18/02/93	set 1	2.72	25.50	0.204	0.60	4
	set 3	1.63	19.40	0.160	0.80	4
Mangamaunu						
17/02/93	set 2	2.25	20.00	0.121	0.50	5
	set 3	1.60	17.20	0.227	0.40	5
	set 4	0.65	10.21	0.063	0.75	5
Saleyards						
16/02/93	set 1	6.66	72.80	0.099	0.50	8
	set 2	5.42	67.60	0.044	0.80	5
	set 3	1.83	25.60	0.098	0.30	5
Birdlings						
16/04/93	set	1.22	13.10	0.124	0.50	6
04/05/93	set	3.21	15.90	0.257	0.30	37
Kaitorete						
05/07/92	set 1	6.00	81.94	0.075	0.80	10
	set 2	3.51	46.36	0.047	0.30	5
23/03/93	set 1	6.16	87.43	0.249	2.70	8
	set 2	4.06	50.54	0.141	1.10	7
	set 3	2.44	68.40	0.053	0.60	4
16/04/93	set 2	5.26	78.50	0.039	1.30	5
	set 3	2.16	43.20	0.160	0.80	8
Hatters Bay						
08/05/93	set	2.37	37.75	0.162	1.10	5
N. Barrytown						
08/05/93	set 1	3.34	61.12	0.106	0.40	6
	set 2	2.64	22.38	0.050	0.76	4
	set 3	0.62	25.74	0.282	0.85	7
Ashburton						
25/09/92	set 1	1.01	32.54	0.158	0.20	5

[a] Relative level of cusp set on the beachface in relation to other sets present, set 1 is highest, set 4 is lowest (not all sets present on a beachface were measured).

[b] Mean beach cusp elevation above MSL.

[c] Coefficient of variation.

4.2. Beach cusp elevation and spacing

For each individual cusp set measured, mean spacing and elevation were determined, with the mean of each set used for the correlations. Spacing and elevation were correlated for the different beach types, as well as both individually and together for two mixed sand and gravel beaches, Leithfield and Amberley. The result is shown in Table 4, which displays the important aspects of the regression analysis, while Fig. 5 illustrates the result for the two beaches. As can be seen from Table 4 and Fig. 5, a strong linear relationship exists between cusp spacing and elevation, with increasing spacing strongly associated with increasing elevation. The regression differs with beach type and also within the same beach type, as evidenced by the different slopes of the regression lines in the equations listed in Table 4.

Table 3
Summary of grain sizes for beach cusp horns and bays

Location	Date	Horn (M_z ϕ)	Bay (M_z ϕ)
Mixed			
Kaitorete	23/03/93	−1.50	0.68
Leithfield	16/12/92	−1.88	1.08
Leithfield	26/03/93 set 3	−1.22	0.73
Leithfield	26/03/93 set 4	−3.26	1.52
Amberley	21/04/93	−3.61	0.97
Amberley	31/05/93	−4.85	−0.85
Amberley	14/06/93	−4.28	−0.05
Waikuku	30/05/93	−2.97	−0.20
Gravel			
Rhino	18/02/93	−3.30	−0.54
Birdlings	04/05/93	−5.68	−4.91
Sand			
Taylors	15/04/93	1.49	1.49
Armers	17/02/93	2.67	2.83
Effingham	05/04/93	2.21	2.22
Effingham	15/05/93	2.90	2.62
Hatters	07/04/93	0.62	1.93

[a] Mean grain size in phi (ϕ) units.

There is a high correlation between cusp elevation and spacing for all beach types ($r = 0.79$), and specifically for Leithfield and Amberley Beaches ($r = 0.81$ and $r = 0.71$, respectively). Sand beaches did not exhibit a high correlation, probably because of the relatively small number of data sets and also the low number of cusp levels present (two at maximum).

The relationships between spacings and elevations are similar for Leithfield and Amberley, and this is probably because they are beaches with similar grain sizes and wave environments. The slight difference in slope of the regression line between the two represents the slightly different sediment conditions present at the two beaches (Table 3). The combined Leithfield and Amberley equation in Table 4 shows that cusp spacings range from 14 to 19 times the cusp elevation with respect to MSL (when C_e is in the range of 0.3 to 1.1 m). If spacing is known, this relationship between cusp spacing and cusp elevation can be potentially used to determine the elevation of formation of a particular set of cusps with respect to MSL.

It is interesting to note in Fig. 5 that two cusp sets were forming below MSL. They were formed during low tide below MSL, and were destroyed on the rising tide. These two sets appear to correspond to the ‘cusplets’ described by Dolan et al. (1974), which form close to the beach step and last no longer than a tidal cycle.

Cusp elevations (and perhaps other dimensions) are a function of wave runup height. Though surf and runup are markedly variable, Kirk (1975) has shown that flows on mixed sand and gravel beaches exhibit strong linear relations between breaker height, runup height and swash length. Kirk (1975) found that runup heights exceed breaker heights and are generally higher for shorter period than for longer period swells (at least in the range $T = 7.5$–10.0 s). It therefore appears that cusp elevation is controlled principally by breaker height, through swash length. In turn, the existence of distinctive cusp ‘sets’ on mixed sand and gravel shores may reflect distinct modes in the wave ‘climate’.

4.3. Beach cusp spacing variance

Measurements of individual beach cusp spacings on the study beaches ranged from 2.6 up to 128 m. Most (75%) of the observed cusp spacings fell in the range from 10 m to 40 m. Spacing variation within individual cusp sets was also apparent. Table 5 summarises regressions for mean beach cusp spacing and elevation against the coefficient of variation of each cusp set. There is a tendency for the regularity of cusp spacing to decrease as mean cusp spacing decreases ($r = -0.41$). Cusp spacing tends to be more regular at higher elevations, and less regular lower on the beachface ($r = -0.43$). These are not very strong trends, and it can be seen that there is a great deal of scatter in the data.

As was noted before, there is a strong relationship between cusp spacing and elevation on the beachface. This relationship is also apparent when cusp standard deviation is regressed against elevation and spacing. They both yield similar correlation coefficients because standard deviation is being regressed against two highly interrelated variables (elevation and spacing). The relationships between cusp regularity and spacing or elevation indicate an important feature of beach cusp development. The cusps higher on the beachface were the more regular, and had the larger spacing. Cusps measured lower on the beach-

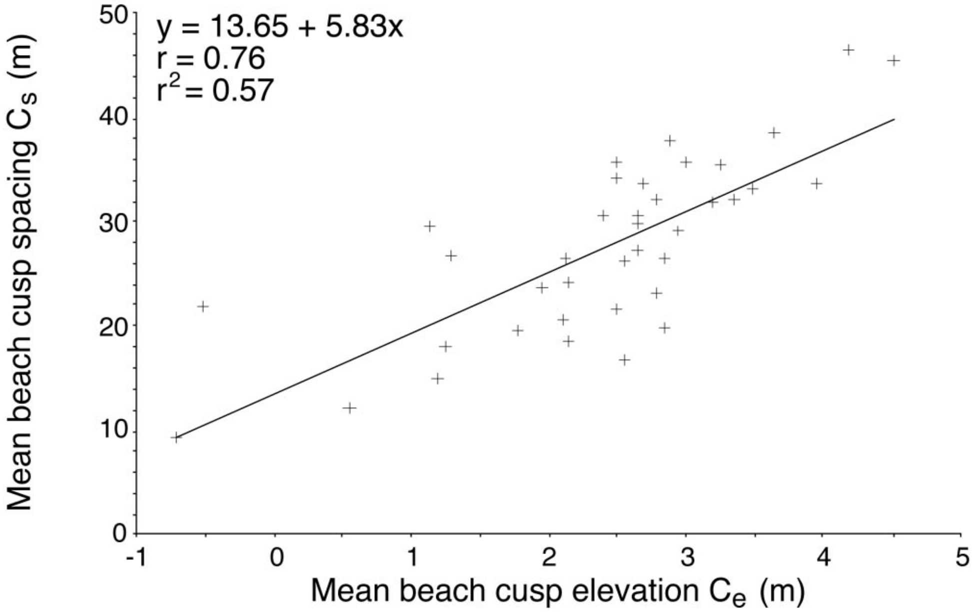

Fig. 5. Regression of mean cusp spacing and elevation for Leithfield and Amberley data.

Table 4
Correlations between mean cusp spacing and elevation for different beach types and for the mixed sand and gravel beach types of Leithfield and Amberley

Beach	r	r_2	Signif. level	n	Line equation
Leithfield	0.80	0.65	0.01	22	$C_s = 14.47 + 6.11C_e$
Amberley	0.71	0.50	0.01	16	$C_s = 12.34 + 5.56C_e$
Leithfield and Amberley	0.76	0.57	0.01	38	$C_s = 13.65 + 5.83C_e$
Sand	0.60	0.36	NS	6	$C_s = 7.67 + 8.45C_e$
Mixed (excl. Leithfield and Amberley)	0.84	0.70	0.01	25	$C_s = 4.66 + 12.09C_e$
All beach types	0.79	0.62	0.01	69	$C_s = 5.74 + 10.23C_e$

face had generally not completed formation, and were still being modified under wave action during subsequent high tides. Inman and Guza (1982) note that some cusps can persist for relatively long times, citing the example of cusps orienting themselves to face into obliquely approaching waves. Cusps lower on the beachface are less regular (Table 5), which is probably a reflection of their being exposed to a wider spectrum of swash from incident waves over several tidal cycles. Cusps forming higher on the beachface are formed during storms when wave set up and meteorological conditions are conducive to large waves travelling further up the beachface. Kirk (1975) noted that there was a linear relation-

Table 5
Elevations of cusp spacing, elevation and standard deviation for all beaches

	r	r^2	Signif. level	n	Line equation
Spacing and C.V.	−0.41	0.17	0.01	68	C.V. = 0.2296 − 0.00198 Sp
Elevation and C.V.	−0.43	0.18	0.01	68	C.V. = 0.2350 − 0.02689 El

C.V. = coefficient of variation.

ship between breaker height and swash length on mixed sand and gravel beaches, with swash length increasing with increasing breaker height. Therefore a possible reason for differences in regularity is that the highest cusps are exposed to large storm waves for relatively short periods (1–2 tidal cycles), while those lower on the beachface are exposed to a grater diversity of swash conditions over longer time periods (>2 tidal cycles).

4.4. Beach cusp spacing and depth

Individual cusp spacing and depth were compared from individual measurements of each dimension. Fig. 6 depicts the relationship between cusp spacing and depth ($r = 0.91$); spacing increases with increasing depth (i.e. $C_s = 2.2C_d$). This indicates that beach cusp spacing and depth are strongly linked, with an increase in spacing being matched by a coincident increase in depth.

4.5. Beach cusp amplitude

Beach cusp amplitudes ranged from 0.05 to 2.70 m. The most commonly observed amplitudes were in the range 0.3 to 0.9 m (92%). There was a difference between amplitudes on different beach types, with amplitude being less pronounced (<0.4 m) on the finer-grained beaches (mean amplitude 0.19 m on sand beaches, other beach types 0.62 m). Beach cusp amplitude varied significantly with cusp spacing and elevation. Table 6 gives a linear relationship, with an increase in spacing being matched by an increase in amplitude, although the correlation coefficient for this relationship is comparatively low ($r = 0.48$). Table 6 also gives a linear relationship between cusp elevation and amplitude. There is a trend that as cusp elevation increases, amplitude also increases, with a correlation coefficient of $r = 0.48$. This low coefficient could be the result of cusp measurements carried out when the beach cusps had not fully

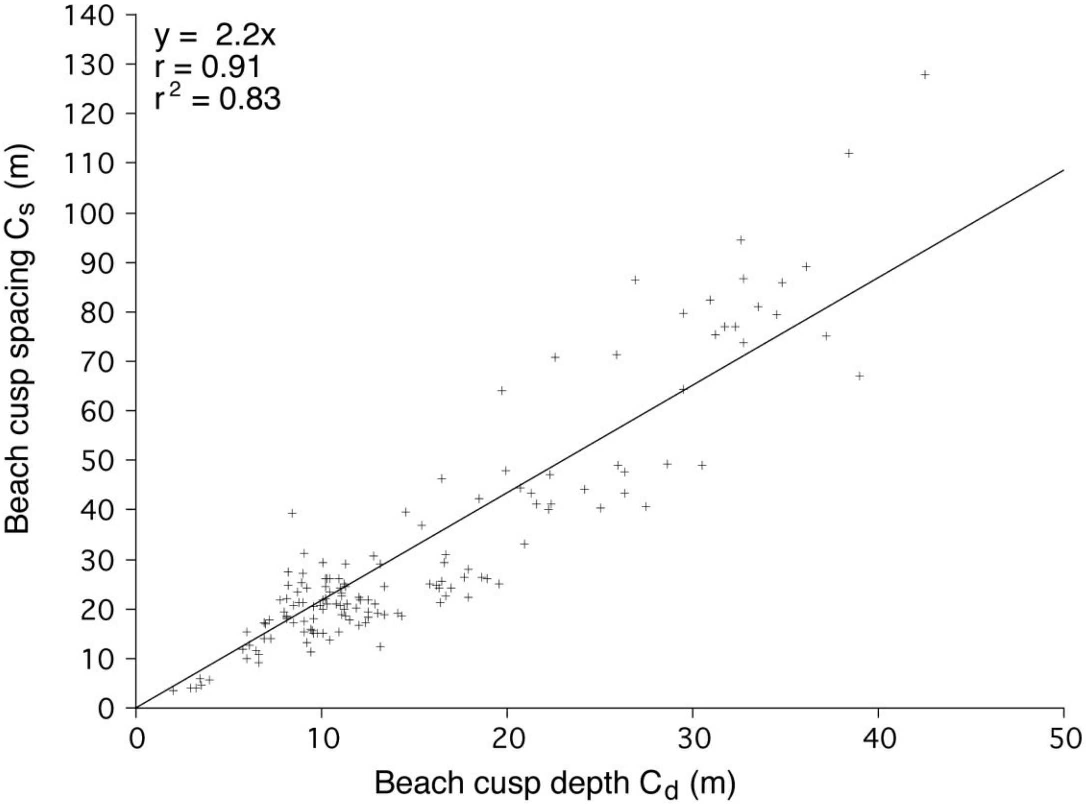

Fig. 6. Regression of beach cusp spacing and depth, forced through origin.

Table 6
Relationships between mean cusp spacing, elevation and amplitude for all beaches

	r	r^2	Signif. level	n	Line equation
Spacing and amplitude	0.48	0.23	0.01	66	$C_a = 0.300 + 0.108C_e$
Elevation and amplitude	0.45	0.20	0.01	66	$C_a = 0.298 + 0.009C_e$

developed, and which therefore had not reached their full potential amplitude, or that cusp elevation may have an inherently low correlation with amplitude, and depends more on other factors (for example, grain size).

Inman and Guza (1982) related cusp steepness (η_c/λ_c) and beach slope (β), to give upper and lower limits for cusp amplitudes based on the assumption that edge-wave activity initiates cusp formation. They provide an estimate of maximum mature cusp amplitude, which can be derived from the following equation:

$$\frac{\eta_c}{\lambda_c \tan\beta} \leq 0.25 \tag{1}$$

while the lower limit is given by:

$$\frac{\eta_c}{\lambda_c \tan\beta} \leq 0.13 \tag{2}$$

where: η_c = cusp amplitude (C_a); λ_c = cusp spacing (C_s); β = beach slope.

Inman and Guza (1982) plotted their own data and data from Guza and Bowen (1981), to ascertain whether it fitted within the upper and lower boundaries supplied by Eqs. 1 and 2. They found that the majority of the data did, and concluded that Eqs. 1 and 2 are reasonable upper and lower limits for cusp amplitudes (Inman and Guza, 1982).

Table 7 lists data collected on South Island beach

Table 7
Beach cusp amplitude and steepness

Cusp ampl. (C_a or η_c) (m)	Cusp spacing (C_s or λ_c) (m)	Beach slope ($\tan\beta$)	$\lambda_c \tan\beta$	Location
Instance (i)				
0.30	29.77	0.087	2.59	Amberley 25/02/93
0.60	30.55	0.087	2.66	Amberley 21/05/93
0.20	26.60	0.052	1.38	Leithfield 02/03/93
0.40	26.46	0.061	1.61	Leithfield 18/04/93
0.30	25.50	0.105	2.68	Gooches 18/02/93
0.30	15.90	0.445	7.08	Birdlings 04/05/93
0.20	11.40	0.101	1.15	Armers 17/02/93
Instance (ii)				
0.35	12.20	0.141	1.72	Amberley 12/01/93
0.70	18.18	0.087	1.58	Amberley 26/03/93
0.80	26.36	0.123	3.24	Amberley 02/04/93
0.70	20.45	0.087	1.78	Amberley 31/05/93
0.40	18.49	0.087	1.61	Leithfield 16/12/92
0.45	14.95	0.096	1.44	Leithfield 12/01/93
0.75	23.32	0.105	2.45	Leithfield 03/02/93
0.30	9.44	0.087	0.82	Leithfield 26/03/93
0.30	4.58	0.123	0.56	Rhino 18/02/93
0.50	13.10	0.268	3.51	Birdlings 16/04/93
0.30	46.36	0.123	5.70	Kaitorete 05/07/92
0.85	25.74	0.141	3.63	N. Barrytown 08/05/93
0.20	32.54	0.079	2.57	Ashburton 25/09/92
0.05	2.95	0.052	0.15	Waikuku 30/05/95
0.10	33.71	0.052	1.75	Effingham 15/05/93

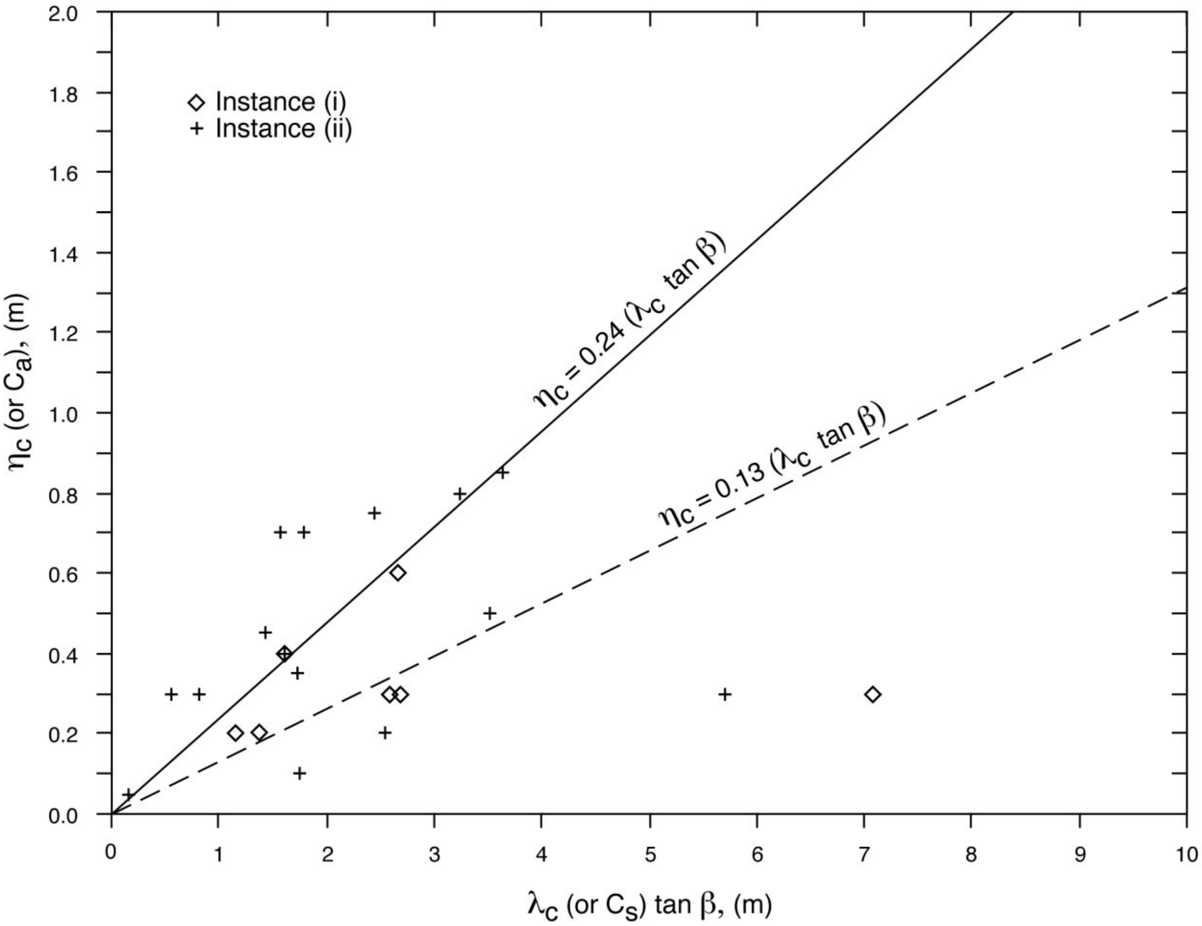

Fig. 7. Cusp amplitude (C_a) versus cusp steepness (C_s tan β), where C_s is beach cusp spacing.

cusp amplitudes and relates them to cusp steepness. Table 7 contains data of two instances of beach cusp observation: (i) when cusps were observed to be forming (i.e. cusps appeared on the beachface); (ii) when cusps were inferred to have formed recently (i.e. after the last high tide).

Fig. 7 details the data from Table 7 graphically, and it can be seen that 47% of instance (i) data, and 20% of instance (ii) data falls within the limits suggested by Inman and Guza (1982).

Taking instance (i) data where cusps were observed to be forming, several points fall below the line of Eq. 2. Inman and Guza (1982, p. 140) suggest that “smaller amplitudes are possible if incident wave conditions are not optimal for cusp growth.” This does not agree with visual observations of South Island beach cusps. Many cusp researchers have reported that edge-wave activity should be suppressed due to the strong viscous effects of plunging breakers (Guza and Inman, 1975: Wright et al., 1979; Inman and Guza, 1982). All of the observed cusps-forming episodes occurred whilst breakers were plunging, and cusps ‘emerged’ on the beachface. The exception was at Birdlings on 4/5/93, where breakers were surging, and this point falls well below the lower limit suggested by Eq. 2.

Examining the instance (ii) data, the majority falls above the upper limit (Eq. 1 line) of maximum mature cusps development suggested by Inman and Guza (1982). This is because on mixed sand and gravel beaches with cusps, the horns comprise significantly larger material than the bays (Table 3).

Therefore, the cusp amplitude relates more to the sediment sizes available on the beach, with the presence of larger sediments giving rise to greater cusp amplitudes. This is supported by beach cusps having small amplitudes on sand beaches (Table 2), combined with the lack of grain size differentiation on sand beaches (Table 3).

5. Conclusions

The investigation of the different cusp dimensions leads to the following three findings:

(1) Cusp dimensions co-vary, and remain proportional to each other under different wave conditions and across beach types. The basic cusp dimensions such as cusp spacing, depth, elevation, and to a lesser extent amplitude remain proportional to each other under differing process conditions. Cusp form thus displays a high degree of regularity from one beach to another.

(2) There are good relationships between all of the variables except cusp amplitude and spacing. Amplitude appears to be more reliant on different factors, such as grain size and beach slope, and does not show as strong a relationship as those between spacing, depth, and elevation.

(3) The most interesting relationship to be observed is that between cusp spacing and elevation on the beachface, which has not previously been quantified. As cusps vary with beach type, each beach is likely to have slightly different correlations between spacing and elevation, due to dissimilar wave conditions, sediments and tides.

This study has demonstrated that cusps of a particular spacing form at specific elevations on the beachface. It has been shown that cusp elevation is controlled by breaker height on mixed sand and gravel beaches. Spacing variation between cusp levels is a function of variability in breaker height and it is expressed through variations in swash length.

The cusp elevation relationship also has the potential to be used as a site-specific proxy indicator of relative sea-level. If the spacing of a set of cusps is known, then an estimate of the elevation above the datum at which they were formed can be derived. This relationship therefore can be used where relict cusps are preserved (for example Worrall, 1969; Shulmeister and Kirk, 1993; Nolan et al., in prep) as a means to recover the elevation above MSL at the time of formation of the relict cusps (i.e. palaeo-sea level). A limitation when applying this relationship to relict cusps is, as shown here, that cusps vary with beach type, and probably with other variables such as the wave conditions and tides of a particular beach.

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