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**The hydrodynamics and morphodynamics  
of selected cusped beaches  
on the eastern Coromandel Peninsula.**

A thesis  
submitted in partial fulfilment  
of the requirements for  
the Degree of  
Master of Sciences in Earth Sciences

By

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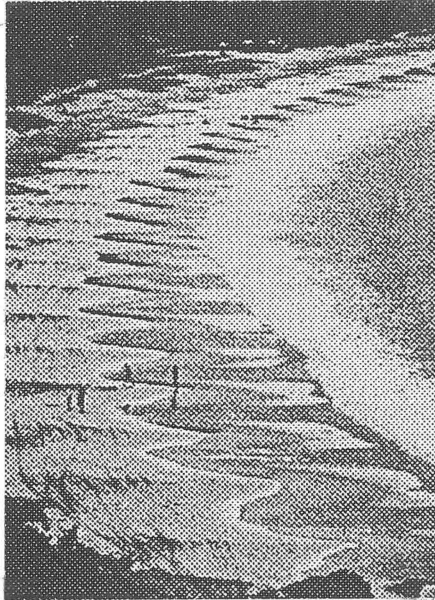
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## *Chapter One*

### *Introduction*

#### **1. 1 Introduction**

Beach cusps are concave seaward-facing features that are rhythmic in the longshore direction (Fig. 1.1). They consist of cusp horns separated by lower sloped cusp embayments where the sediment of the horn is generally coarser than that of the embayment. They are located in the swash zone, near the high tide mark, and form a series of undulations along the beach. Cusp spacing, the distance between consecutive cusp horns, is quasi-uniform. The onshore topography is mirrored offshore with deltas forming at the base of each embayment and troughs forming at the base of each cusp horn (Fig. 1.2).

Beach cusps have been of interest to coastal scientists for more than a century and their study has generated a vast amount of literature. The main emphasis of the numerous investigations has been the causative mechanism of the uniform longshore spacing; the description of the associated hydrodynamics and sediment transport; and the development of predictive relationships for their spacing. Cusp morphodynamics may have important implications to the form and scale of nearshore circulation patterns and wave dynamics (Guza and Inman, 1975; Inman and Guza, 1982; Seymour and Aubrey, 1985).

Although they are common, and despite numerous investigations, the process of beach cusp formation is not yet fully understood making them one of the most intriguing coastal morphological features.



Fig. 1.1 Beach cusps on Buffalo Beach, Coromandel Peninsula (photo: Terry Healy).

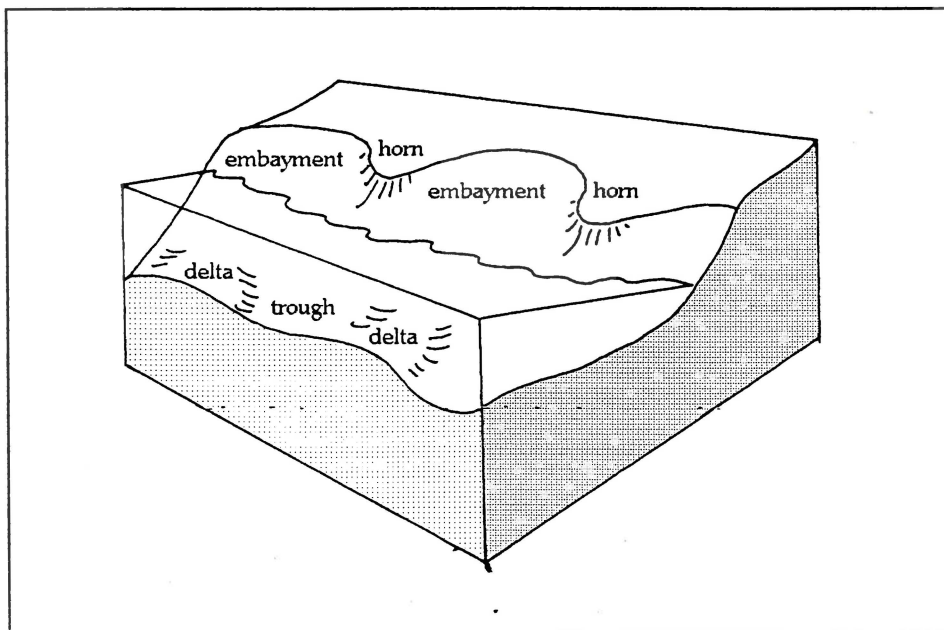


Fig. 1.2 Schematic diagram of the morphology of a cusped beach.

## 1.2 Literature review

Despite much debate over the initiation and formation of cusps, several generalisations regarding their morphological characteristics and possible causative mechanisms can be gained from the literature. Expanding on such assumptions forms the basis of the objectives of this study.

Most commonly noted is that beach cusps have a uniform spacing along a beach. Komar (1973) observed small cusps with spacing less than a metre whilst Longuet-Higgins and Parkin (1972) generated similar size cusps in a wave basin. Shepard (1952) measured 'giant cusps' that ranged up to 1,500 m between adjacent horns. Commonly, spacing is from 1-100 m (Russel and McIntyre 1965; Dyer, 1986; Antia, 1987).

Komar (1976) and Antia (1987) note that two or more levels of cusps can occur on the same beach, those higher up on the beach having a larger cusp spacing. Russel and McIntyre (1965) observed two and three sets of cusps on various occasions during their investigations of cusped beaches. Williams (1973) observed three rows of cusps on Hong Kong beaches. The levels of cusps higher on the beach with larger cusp spacings are thought to be due to larger storm waves (Russel and McIntyre, 1965; Schwartz, 1972; Dalrymple and Lanan, 1976).

Shepard (1963) and Otvos (1964) noted that cusp length gradually decreases from areas of high energy to low energy.

Beach cusps form in all types of beach sediment (Komar, 1976). The cusp horn is of coarser sediment than the embayment (Russel and McIntyre, 1965). Longuet-Higgins and Parkin (1962) note that this difference results in a higher permeability of the horns relative to the embayments. They state that the distinct sediment sizes accentuate the erosional and depositional processes because percolation rates in the bays are low favouring erosion, while more percolation occurs in the coarser material of the horn, lowering velocities and favouring deposition. Sallenger (1979) also agrees that cusp formation is a result of both erosion and accretion but notes that their development results in mostly net accretion. Otvos (1964), Gorycki (1973), Guza and Inman (1975), Inman and Guza (1982), Antia (1987) and Miller *et. al.* (1989) concluded that beach cusps are a result of accretion and erosion. However, Komar

(1973), Schwartz (1975) and Sander *et. al.* (1976) suggest that cusps are a result of only accretion while Smith and Dolan (1960) observed cusp formation as being a result of only erosion.

Water circulation over the cusped form involves the swash run-up dividing at the horns, converging in the troughs and the backwash being met by the next run-up forcing the swash onto the horn (Bagnold, 1940; Komar, 1976, Sallenger, 1979; Pethick, 1984). This circulation of swash maintains the cusped form.

It is suggested that the formation of cusps is related to accretionary cycles on beaches (Otvos, 1964; Williams, 1973; Dubois, 1978; Sallenger 1979). Cusps are observed to form with the transition from high energy to low energy (Komar, 1976). Antia (1987) found that cusps were most prevalent during calm conditions. Sallenger (1979) observed the onshore migration of a bar as energy fell which was then modified by swash to form cusped shapes. Kaneko (1985) also observed cusp formation as modification of a beach ridge in laboratory experiments.

Seymour and Aubrey (1985) observed that cusps persisted until some significant change in wave conditions and found that large waves destroyed cusps. Longuet-Higgins and Parkin (1962) state that when wave height is too great for the vertical dimensions of the cusps, swash tends to sweep over the cusps and destroy them. Miller *et. al.* (1989) observed cusps during a large storm at Duck, North Carolina and found that storm waves destroyed cusps leaving a post-storm planar beach. Within 24 hrs after the storm, cusps reformed sequentially along the beach in the direction of longshore transport.

Theories explaining the regular spacing of cusps include the instability of breaking waves (Cloud, 1966), the role of incident waves and swash (Longuet-Higgins and Parkin, 1962; Gorycki, 1973; Dalrymple and Lanan, 1976; Dean and Maurmeyer, 1981) and the influence of topography on cusp formation (Otvos, 1964; Williams, 1973; Dubois, 1978; Sallenger, 1979). Longuet-Higgins and Parkin (1962) and Dean and Maurmeyer (1981) found a correlation between the swash excursion distance and cusp spacing. Dalrymple and Lanan (1976) also concluded that swash has a role in cusp formation. Russel and McIntyre (1965), however, suggest that cusp spacing is dependant on the degree of beach exposure and the sea state.

More recent investigations have attributed the formation and spacing of cusps to the action of edge waves which are free surface gravity waves that propagate along a sloping beach where energy is trapped in the nearshore zone by refraction, resulting in sinusoidal variation in wave height, in the longshore direction. Edge waves are thought to play an important part in coastal sedimentation (Bowen and Inman, 1971; Huntley and Bowen, 1975; Guza and Thornton, 1985; Holman and Sallenger, 1986). Many studies provide theoretical and observational evidence for edge waves being the triggering mechanism for cusps, providing the initial perturbation for cusp spacing and spatial distribution. Guza and Davis (1974) state that a standing incident wave transfers energy to edge waves through a weak resonant interaction. An edge wave with a period twice that of the incident wave is preferentially excited (Galvin, 1965; Bowen and Inman, 1969; Huntley and Bowen, 1973; Guza and Davis, 1974). Most commonly, investigators conclude that cusp spacing is a result of a subharmonic edge wave, where the edge wave period is twice the period of the incident wave period (Galvin, 1964; Bowen and Inman, 1969; Bowen and Inman, 1971; Huntley and Bowen, 1973; Komar, 1973; Guza and Inman, 1975; Gaughan and Komar, 1977; Sallenger, 1979; Guza and Bowen, 1981; Inman and Guza, 1982; Wright, 1982; Kaneko, 1985; Seymour and Aubrey, 1985; Miller *et. al.*, 1989).

Edge waves have been investigated using current meters to measure the nearshore velocity field. Oltman-Shay and Guza (1987) used an array of current meters and found oscillation they interpreted as edge waves and concluded that such wave motion could contribute significantly to both the longshore velocity and run-up components of the nearshore infragravity wave field. Sasaki and Horikawa (1975), Huntley *et. al.* (1981), Holman (1981) and Bowen and Huntley (1984) also found edge wave motion in the spectra from current meters placed in the nearshore zone.

Guza and Bowens' (1976) laboratory investigations found that subharmonic edge waves are primarily driven by swash. They found that subharmonic edge waves do not occur where the breakers are spilling or plunging but do occur when the wave is surging. Galvin (1965) also suggests that the generation of edge waves is dependant on wave characteristics, stating that resonance disappears when the wave breaks cleanly. Kaneko (1985), using a steep laboratory beach covered in glass beads, found that surging and semi-plunging breakers were needed for cusp formation. Short (1979) agrees with this, having evidence to support that when there is

an initially planar beach accompanied by low surging breakers, rhythmic variation in the swash set up by subharmonic edge waves are likely mechanisms for the regularity of cusp spacing.

Guza and Inman (1975) found cusps were formed in a wave tank by subharmonic edge waves and only when the incident wave was strongly reflected from the beach. Wright (1984) also found a relationship between beach state and cusp formation stating that cusps form on reflective beaches where the incident wave is reflected from the beach face. Wright (1982) found that subharmonic edge waves consistently occurs on reflective beaches where they cause cusps spaced at one half of the edge wave wavelength. On flatter, more dissipative beaches, lower frequency edge waves occur. Huntley and Bowen (1973) note that the hydrodynamics of steep and shallow beaches differ widely and found subharmonic edge waves on steeper beaches but not on less steep beaches and, like Wright (1982), found lower frequency motion on the less steep beaches. Antia (1989) found that cusp existence and extinction is primarily controlled by foreshore slope and notes that cusps were more common and persistent on reflective sections of the beaches investigated. Sallenger (1979) also found that low energy reflective environments were needed for cusp formation.

Edge waves, and non-trapped standing waves can occur from incident wave frequencies to low 'surfbeat' (100-300s) frequencies (Huntley, 1976; Guza and Bowen, 1977; Chappell and Wright, 1979; Holman *et. al.*, 1979 and Wright *et. al.*, 1979a, 1979b). Bowen and Guza (1978) state that 'surf-beat', the beating between pairs of incoming waves, leads to the growth of edge waves and say that 'surf-beat' is predominantly an edge wave phenomenon. Wright *et. al.* (1987) concludes that 'surf-beat', or wave groupiness, effects short term morphological responses of a beach. 'Surf-beat' is thought to be significant in the nearshore (Suhayda, 1972; Huntley and Bowen, 1975; Bradshaw, 1980; Guza and Thornton, 1982) and there is a correlation between 'surf-beat' and edge waves (Suhayda, 1972; Huntley, 1976; Sasaki, 1978; Huntley *et. al.*, 1981; Holman, 1981) which in turn may control the spacing of beach cusps.

### 1.3 Objectives

The aim of this investigation is to examine the hydrodynamics and morphodynamics of the nearshore zone at selected cusped eastern Coromandel beaches (Fig. 1.3), expanding on

previous work regarding beach cusps. By investigating the interrelationships between the littoral sediment transport and distribution, the wave characteristics and nearshore circulation patterns, attempts can then be made to relate cusp initiation, development and maintenance to these parameters. The beaches in this study were selected because they vary in terms of aspect, sediment size, wave climate and beach shape yet all exhibit beach cusps at some time.

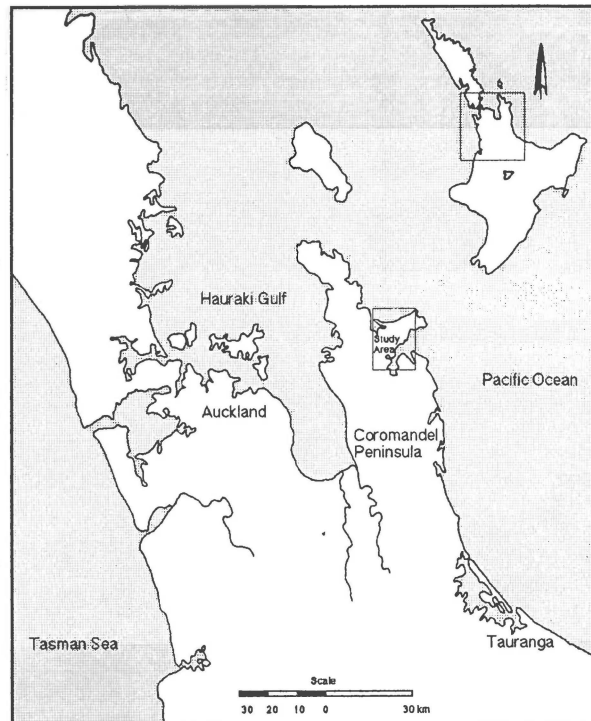


Fig. 1.3 Location map illustrating the study area on the eastern Coromandel Peninsula.

Specific objectives of this study are delineated in respect to the literature cited above. The primary aim is to contribute to the knowledge regarding beach cusps, in a New Zealand setting. The specific aims are:

1. Describe cusp morphology at the investigated beaches and to establish a database of morphodynamic, hydrodynamic and sediment characteristics associated with the cusped beaches.
2. Investigate the temporal distribution of beach cusps on selected beaches and the parameters that influence the existence and extinction of cusps.

3. Statistically analyse the parameters measured to determine which are associated with the physical characteristics and the spatial and temporal distribution of cusps.
  
3. Investigate the theory of edge waves and the application of the theory in the prediction of the spacing of beach cusps. Assess whether the theory is applicable for the cusped beaches investigated on the eastern Coromandel.
  
4. Classify the beaches investigated in terms of the Wright and Short beach state classification model and discuss how the morphological beach state can be related to the spectral characteristics of edge waves and cusp formation.
  
5. Undertake direct measurements of the nearshore velocity field at selected beaches using a S4 current meter to investigate low frequency motion.
  
6. Use spectral analysis to attempt to identify edge wave and 'surf beat' oscillations in the onshore-offshore and alongshore spectra and to investigate whether any oscillations at these frequencies can be related to the spacing of beach cusps. To assess whether the spectra is typical for the type of cusped beaches investigated in respect to the Wright-Short model.
  
7. Use hincasting techniques and wave refraction modelling to assess the effects of wave energy changes along a beach on the spatial distribution of cusps.
  
8. Discuss the interrelationships between the hydrodynamics and morphodynamics of the cusped beaches and contribute to the knowledge regarding the origin, formation and maintenance of beach cusps.

## **1.4 Thesis structure**

Chapter 1 outlines the thesis topic including a literature review of previous investigations regarding beach cusps and the theories devised to explain cusp initiation and spacing. The objectives of the study are detailed in respect to this previous work.

Chapter 2 gives an overview of the seven cusped beaches selected for the investigation and describes how they differ in terms of their morphology, hydrology and sediment characteristics.

Chapter 3 tabulates and describes the data gathered regarding the characteristics and the temporal and spatial distribution of cusps at each beach. The data is statistically analysed to assess the degree of association between the various parameters.

Chapter 4 discusses the theory of edge waves and details how the theory can be used as a predictive model for the spacing of beach cusps. The beaches investigated are assessed in terms of the theoretical existence of edge waves and discusses whether the spacing of the cusps can be theoretically explained by edge waves.

Chapter 5 expands on the theory that edge waves may be responsible for the spacing of cusps and investigates the theoretical characteristics of edge waves as being dependant on the beach state. The beaches are classified in term of the Wright Short model to further investigate if the existence of edge waves is feasible on the beaches studied.

Chapter 6 analyses current meter data using spectral analysis and compares the resultant spectra with examples from the Wright and Short model to investigate the nearshore hydrodynamics and to assess whether the spectra is characteristic of the beach states determined in Chapter 5. The spectra is also described in terms of long period oscillations to attempt to ascertain if edge wave motion exists. This is discussed in respect to the spacing of the cusps.

Chapter 7 uses hindcasting techniques to predict the wave period, wave height and swell direction that formed cusps in Mercury Bay in late May, 1992. The predicted conditions are used in a wave refraction model. Energy changes along the length of the beaches are investigated in respect to wave refraction, diffraction and the spatial distribution of beach cusps.

Chapter 8 discusses the interrelationships between the parameters and processes investigated and summarises the findings of the study. Limitations of the investigation are noted and areas where further research may be carried out are discussed.



## *Chapter Two*

### *Study location*

#### **2.1 Introduction**

Cusps are common morphological features on north-eastern Coromandel Peninsula beaches. The beaches in this study (Hahei, Cooks, Maramaratotara, Buffalo, Wharekaho, Kuaotunu West and Rings Beaches) were selected because they vary in terms of aspect, sediment size and wave climate yet all exhibit cusps at some time. No previous work has been undertaken to characterise beach cusps in this region but their presence is noted by Smith (1980), Healy *et. al.* (1981) and Fulton (1991).

#### **2.2 Physical setting**

The Coromandel Peninsula is an uplifted horst block covered by recent volcanic air fall deposits (Skinner, 1976). The coastline is characterised as a headland-bay coast where headlands are separated by narrow, shallow embayments (Fig. 2.1). These embayments differ markedly in terms of beach state depending on the beach length, width, aspect, sediment size and the wave climate (Fulton, 1991).

Mercury Bay is a semi-enclosed composite embayment. The beaches within Mercury Bay are headland controlled, crenulate-shaped beaches and have formed in response to wave refraction patterns within the bay. Buffalo Beach is a large bay barrier that fronts approximately 6.0 km of parallel dune ridges (Fig. 2.2). Cooks Beach (Fig. 2.3) is a bay barrier that fronts Holocene dune

ridge progradation. Maramaratotara (Fig. 2.4) and Wharekaho (Fig. 2.5) are pocket beaches resulting from refracted swell waves (Fulton, 1991).

The other beaches investigated fall to the north and south of Mercury Bay. Rings Beach is a relatively sheltered 0.7 km long bay barrier beach (Healy *et al.*, 1981) that has a northerly aspect and is bounded at either end by cliffs (Fig. 2.6). Kuaotunu West Beach (Fig. 2.7) is geomorphically similar to Rings Beach (Healy *et al.*, 1981) but is divided into two sub-systems by a headland and a reef. Hahei is a 1.5km bay barrier beach (Fig 2.8) that has a northeasterly aspect (Abrahamson, 1987).

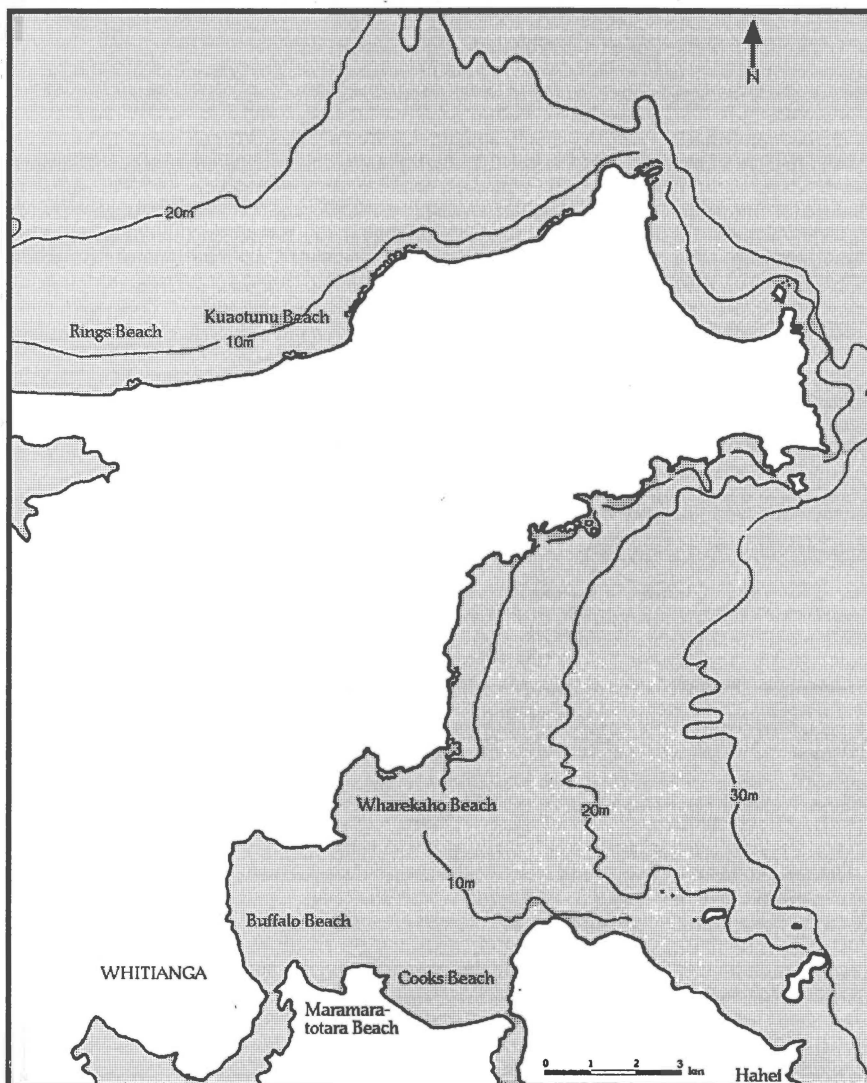


Fig. 2.1 The locations of the often cusped beaches, on the eastern Coromandel Peninsula, that are the focus of this study.



Fig 2.2 Buffalo Beach (photo: Terry Healy)



Fig. 2.3 Cooks Beach (photo: Terry Healy)



Fig 2.4 Maramaratotara Beach (Photo: Terry Healy)



Fig. 2.5 Wharekaho Beach



Fig 2.6 Rings Beach (photo: Terry Healy)



Fig 2.7 Kuaotunu Beach (note the gravel cusps on the beach face)



Fig 2.8 Hahei Beach

### 2.3 Wave climate

The eastern Coromandel Peninsula is subject to a temperate climate and conditions are generally warm and humid (Hume and Dahm, 1991). Humid airstreams from the tropical Pacific Ocean produce heavy rainfall (Abrahamson, 1987) ranging from 1500 mm to 1800 mm per annum (Maunder, 1974). Figure 2.9 summarises climatological data for the study area. Wind velocity summaries show a prevalence of prevailing westerlies but also contain a significant proportion of winds from the northeast and easterly directions. As the study area is exposed to these directions, it is susceptible to wind and waves generated by depressions passing over New Zealand.

Pickrill and Mitchell (1979) note that the approach direction for waves ranges from north through to the east, where the dominant wave is from the northeast. Harris (1985) recorded average significant wave heights of approximately 1.0 m. Wave periods average 6.4 s in open waters and range between 4.0 and 9.0 s. Hay (1991) states that long period swell waves (8.0-

12.0s) originate from depressions north or northeast of New Zealand and hence arrive from the north.

Fulton (1991) states that Rings Beach has the same wave climate and exposure as nearby Matarangi Beach where the breaking wave height ( $H_b$ ) < 0.7 m and wave period ( $T$ ) = 7.0-10.0 s. Kuaotunu West has the same aspect and exposure as Rings Beach and has similar wave characteristics but is sheltered by an offshore reef.

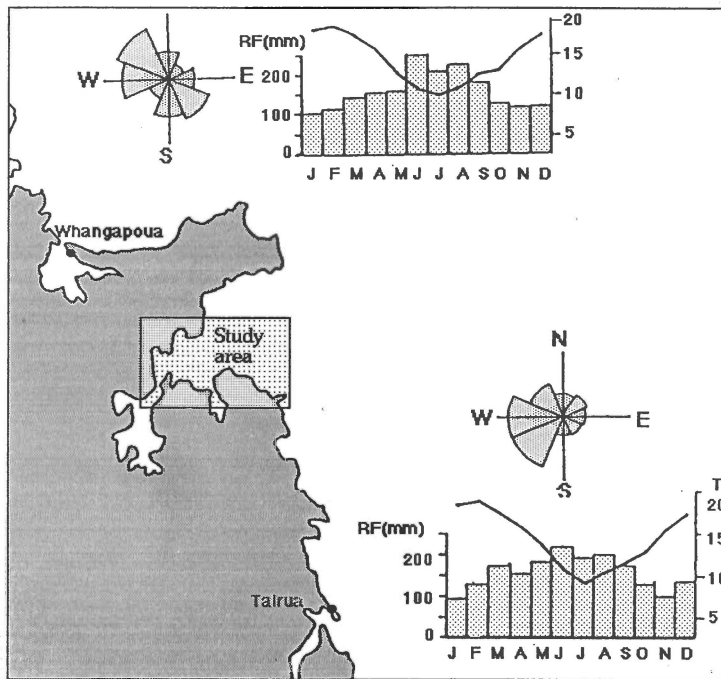


Fig. 2.9 Climate patterns for the eastern Coromandel Peninsula (Abrahamson, 1987).

Hahei has a low energy environment ( $H_b=0.5$  m) and offshore islands shelter the beach. Fulton (1991) notes that during episodic easterly storms, wave heights are in excess of 2.5 m. Buffalo Beach is characteristically of lower energy than the preceding beaches as sea and swell waves entering Mercury Bay are reduced in height in response to refraction, diffraction and the shoaling of the sea bed. Significant diffraction occurs in the lee of the headlands which results in the lateral dispersion of wave energy, the effect of this being most evident at the northern end of Buffalo Beach (Smith, 1980). Swell waves change in character from very low energy in the north to moderate at the southern end of the beach. Wharekaho and Maramaratotara have a similar aspect to Buffalo Beach and similar wave parameters although energy is higher. The southern end of Wharekaho receives more wave energy than the north whereas the northern end of Maramaratotara is exposed to episodic northeast storms (Smith, 1980).

## 2.4 Tides

The tidal wave in Mercury Bay is asymmetric, of semi-diurnal form, with a mean spring tidal range of 1.62 m. Harris (1985) notes that small diurnal variations in height do occur.

Tidal patterns are modified within Mercury Bay where near-surface currents during tidal flows form a clockwise circulation gyre. Oceanic waters enter the southern side of the bay, mix with Whitianga Harbour waters before leaving along the northern headland (Smith, 1980).

Table 2.1 Characteristics of the investigated Coromandel Beaches (~ Healy *et. al.*, 1981; \* Fulton, 1991; † data from this investigation).

Beach	H <sub>b</sub> (m)	T <sub>i</sub> (s)	Aspect	Sediment characteristics	Beach gradient (°)†	Cusp characteristics†
Buffalo	0.4 <sup>†</sup>	7-11 <sup>†</sup>	east	fine sand with significant amounts of coarse sand~	3.0	shell cusps
Wharekaho	0.6 <sup>†</sup>	7-11 <sup>†</sup>	east	medium sand, often laminae of heavy minerals~	7.5	sand cusps
Maramar-atotara	0.6 <sup>†</sup>	7-11 <sup>†</sup>	north east	coarse on dunes and medium elsewhere~	5.5 - 6.0	sand cusps
Kuaotunu west	<0.7 <sup>*</sup>	7-10 <sup>*</sup>	north	gravel and cobble over medium sand~	3.0	gravel cusps
Rings	<0.7 <sup>*</sup>	7-10 <sup>*</sup>	north	well sorted medium to coarse sand~	5.5 - 6.0	sand cusps
Cooks	0.3 <sup>†</sup>	7-11 <sup>†</sup>	north	medium to fine sand~	3.0	sand cusps
Hahei	0.5 <sup>*</sup>	7-11 <sup>†</sup>	east	well sorted medium sands <sup>*</sup>	5.5 - 6.0	sand cusps

Table 2.1 summarises the general morphodynamics and hydrodynamics; and sedimentological characteristics of the beaches investigated.

These basic characteristics of the cusped beaches are expanded on in Chapter Three by analysing sediment, morphological and hydrological data collected during this study.



## *Chapter Three*

# *Beach cusp morphological and distributional characteristics*

### **3.1 Introduction**

Cusp morphology varies between beaches with each beach having a characteristic beach cusp topography as a result of the interaction between different wave climates, beach shape and aspect, and sediment characteristics.

In this chapter, beach cusps are described in terms of their dimensional and sediment characteristics and in terms of their spatial and temporal distributions. The interactions between variables characterising beach processes are analysed statistically, using multivariate analysis, to assess those parameters associated with the development of a cusped beach.

### **3.2 Variables**

Several variables were measured to describe the morphology of the cusped beaches and these are illustrated in Figure 3.1. The variables can be separated into related groups - wave, sediment and morphological characteristics. The variables and the methods by which they were measured are described below.

#### **3.2.1 Wave variables**

Wave characteristics are important in the development and the nature of beach morphology. Changes in wave height, steepness and period, and the type of breaking wave influence the

movement of sand and the degree of sorting in the nearshore zone and may subsequently influence the development of cusp morphology. Eight wave variables were measured and analysed.

Breaking wave height ( $H_b$ ) (m) was estimated visually as a measure of the energy reaching the beach face. Larger waves are thought to produce cusps further up the beach face with a greater spacing than those cusps associated with smaller waves (Dalrymple and Lanan, 1976).

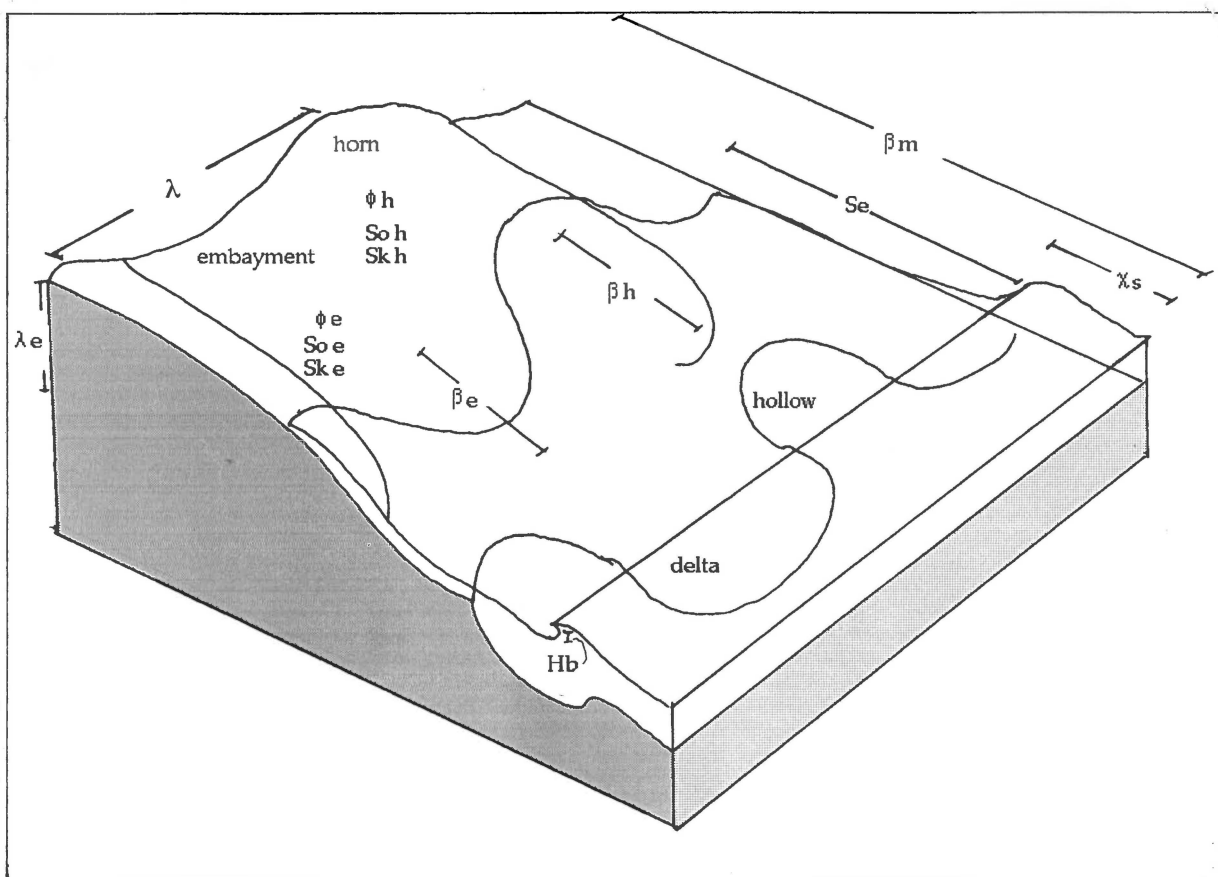


Figure 3.1 Variables investigated on the cusped beaches of the eastern Coromandel.

The incident wave period ( $T_i$ ) (s) was determined by averaging the time taken for 10 wave crests to pass a fixed point. Cusps have been noted to form when the wave period is long (Komar, 1976).

Wave steepness ( $\frac{H_b}{L_s}$ ) was calculated using the shallow water wave length ( $L_s$ )

$$L_s = T\sqrt{g h_b} \tag{3.1}$$

where:  $T_i$ =wave period (s)

$g$ =acceleration of gravity ( $9.81 \text{ m/s}^{-2}$ )

$h_b$ =water depth at breaking (m).

Wave steepness is an important parameter for determining whether a beach will erode or accrete. Steeper waves cause erosion of the beach. King (1972) suggests that waves with a steepness  $>0.03$  generate seaward flowing currents while those flatter waves produce shoreward currents.

Water depth at breaking ( $h_b$ ) is calculated by the McCowan (1894) criteria:

$$h_b = \frac{H_b}{0.78} \quad 3.2$$

Wave type (WT) is a function of wave steepness, beach slope and sediment texture and can be predicted using Galvin's (1968) dimensionless model:

$$H_b / (g T_i^2 \tan \beta), \quad 3.3$$

where:  $\beta$  = beach slope ( $^\circ$ ).

Breakers can be of three types; spilling breakers associated with low slope beaches and steep waves ( $>0.068$ ); plunging breakers associated with steeper beaches and moderate steepness waves ( $0.003$ - $0.068$ ) or surging breakers which occur on very steep beaches with waves of low steepness ( $<0.003$ ). Breaking wave type is considered an important factor in this study because the type of wave breaking on the beach effects the nearshore hydrodynamics and the nature of any wave resonance that may exist.

The surf zone width ( $\chi_s$ ) (m) is defined as the region of the nearshore zone where waves break and the width was estimated visually from the beach. The width of the surf zone was noted because it is an indicator of the amount of energy dissipated before reaching the beach face. It is also influenced by wave energy and the slope of the nearshore zone and determines the type breaking wave.

Swash excursion ( $S_e$ ) (m) was measured as the distance from wave breaking to the furthest point of swash run-up on the beach face. The swash distance was measured because has been suggested by Longuet-Higgins and Parkin (1962) and Dean and Mauremeyer (1981) that swash may be the controlling mechanism for the spacing of cusps.

Sallenger (1979) found that cusp spacing is dependent on the degree of beach exposure. In this study, the degree of exposure (Exp) is estimated qualitatively ranking each beach (1 (sheltered) through 5 (exposed)) defining exposure as being a function of observed wave energy, fetch length and beach aspect.

### 3.2.2 Sediment variables

Particle size ( $\phi$ ) and hydraulic fall velocity ( $\omega$ ) of beach sediments are important in determining the shape of beach profiles and the morphological units present on a beach (Fulton, 1991). Mean particle size, hydraulic fall velocity, sorting and skewness of both horn and embayment samples for each beach were determined using the Rapid Sediment Analyser (R.S.A) at the University of Waikato (see Appendix A for more detail on the methodology). This was undertaken to assess how variance in sediment characteristics influences cusp characteristics.

As sediment size increases it's transportability decreases. Particle size closely reflects the energy level of the wave processes working on the sediment. The coarseness of the sediment is indicative of the degree of turbulence and wave energy dissipation (Komar, 1976). For example, fine sand may indicate lower energy. The mean grain size controls the amount of percolation into the sediment.

Sorting ( $S_o$ ), or the standard deviation from the mean sediment size, gives an indication of the spread of grain sizes around the mean. It is a measure of the uniformity of size of the sediment and the uniformity is a result of sediment transport processes. Poorly sorted material indicates that little selection of grains has taken place during the transport and deposition of the material. Well sorted material indicates selective action by wind and waves which transport and deposit only a limited range of grain sizes (Komar, 1976).

Skewness ( $Sk$ ) is a measure of the symmetry of the sample around the mean expressed as a positive or negative value about the symmetrical value of 0 and is an indicator of the history of the sample. A normal distribution gives a symmetrical curve and the skewness is 0. A negatively skewed sample has an asymmetric curve with a dominance of coarse material. A positive skew is indicative of an excess of fines due to an addition of fine sediment or the removal of coarser sediment.

Grain size, the degree of sorting and skewness are important parameters when describing cusp morphology because they reflect the amount of energy and work done in the nearshore zone and, subsequently, the extent of cusp development.

### 3.2.3 Morphological variables

Seven morphological variables associated with a cusped beach were measured to assess morphology differences between cusped beaches.

Slope determines the amount of energy imparted on the beach face and this in turn exerts an influence on the processes in the swash zone. Three slopes were measured to represent the gradient of the cusped beach. The cusp horn ( $\beta_h$ ) and cusp embayment ( $\beta_e$ ) slopes were measured from beach profile data. The mean subaerial effective beach slope ( $\beta_m$ ), defined as the area from the high tide mark to near the low tide mark, was estimated from profile data as a mean of the different slopes on the beach face.

Cusp spacing ( $\lambda$ ) (m) was calculated by averaging the measured spacing of cusps present on the beach with the spacing being defined as the distance between adjacent cusp horns.

Cusp elevation ( $\lambda_e$ ) (m) is defined as the vertical distance between the highest point on the cusp horn to the lowest point in the cusp embayment and was calculated from profile data.

The percentage variation from the mean of cusp spacing ( $\% \lambda_v$ ) was calculated from the standard deviation from the mean of the sample.

The percentage of the beach cusped ( $\% \lambda$ ) was estimated visually at the time of observation.

### 3.2.4 Other variables

The tidal height (TH) (m) for each day of observation was used for assessing tidal effects. Tidal range modulates surf zone processes by causing temporal variations in the surf zone width and breaker position.

## 3.3 Cusp characteristics

### 3.3.1 Wave characteristics

Data regarding the wave dynamics at each beach are presented in Table 3.1.

Table 3.1 Wave variables measured to describe the wave conditions for each observation period (Mara. = Maramaratotara Beach)

Beach	Date	$H_b$	$T_i$	$H_b/L_s$	WT	$h_b$	$\chi_s$	Exp
Buffalo	3/91	0.70	9.80	0.02	0.011	0.90	9.00	1
Buffalo	4/91	0.45	11.0	0.02	0.0072	0.58	9.00	1
Buffalo	7/92	0.55	8.35	0.03	0.018	0.71	10.0	1
Cooks	5/92	0.33	10.0	0.02	0.0064	0.42	7.80	1
Hahei	5/92	0.48	10.0	0.02	0.0050	0.62	3.50	4
Hahei	8/92	0.40	9.00	0.02	0.0049	0.51	2.50	4
Kuaotunu	3/91	0.30	11.0	0.01	0.0048	0.38	8.00	3
Mara.	3/92	0.35	10.0	0.02	0.0033	0.45	3.00	2
Mara.	5/92	0.60	10.0	0.02	0.0067	0.77	3.00	2
Mara.	7/92	0.73	7.90	0.03	0.011	0.94	2.00	2
Mara.	8/92	0.10	9.00	0.01	0.0012	0.13	3.00	2
Rings	3/91	0.30	11.0	0.01	0.0026	0.38	6.00	3
Rings	3/92	0.50	11.0	0.02	0.0043	0.64	7.00	3
Rings	5/92	0.30	10.0	0.02	0.0031	0.38	10.0	3
Rings	8/92	0.40	9.00	0.02	0.0052	0.51	9.00	3
Wharekaho	5/92	0.48	10.0	0.02	0.0039	0.62	2.0	5
Wharekaho	7/92	0.70	7.90	0.03	0.0081	0.90	1.5	5

Table 3.1 shows that wave height varies between beaches and also over time at each beach. Absolute values are not indicative of relative changes between beaches, in terms of wave energy, as not all beaches were investigated at the same time. 'Exposure' values give a better comparison. In general, of the beaches studied, Wharekaho Beach has the highest wave energy, being exposed to the east. Maramaratotara and Buffalo Beaches have the same aspect as Wharekaho but Maramaratotara is sheltered by Shakespeare Cliff while Buffalo beach is of even lower energy because wave heights are greatly reduced by refraction and diffraction (Smith, 1980). Rings Beach has similar wave energy to Hahei although Hahei is somewhat sheltered by offshore islands. Cooks Beach has a similar wave climate to Buffalo Beach, but is exposed more to the north-east. Kuaotunu Beach has similar wave heights to Rings but energy is dissipated by offshore rocks. Wave energy and diffraction and refraction are investigated in more detail in Chapter Seven. This is in general agreement with the observations of Healy *et. al.* (1981) and Fulton (1991).



Fig. 3.2. Surging breakers on cusped Hahei Beach. Note the narrow surf zone, and the waves breaking close to the beach face and surging up the beach face.

Wave types on the investigated beaches were toward the surging end of Galvin's (1968) scale, where waves break close to the shore line and swash surges up the beach face. Rings, Wharekaho and Maramaratotara and Hahei Beaches (Fig 3.2) were consistently the most

surging. Cooks and Buffalo Beaches had more dissipative conditions and the breaking wave was more plunging in nature. Wave type is a function of wave height, period and beach slope, where beach slope appears to be the most influential - the steeper beaches having more surging waves.

In most cases, wave steepness values were under 0.03 suggesting the cusps were existing under accretional conditions. The exception was at Buffalo, Maramaratotara and Wharekaho Beaches during July 1992, where the waves were steep enough to be erosive (values  $>0.03$ ) and were accompanied by shorter wave periods ( $< 8.0$  s). The waves during this observational period were more plunging in nature.

For each beach, waves broke in less than 1.0 m of water adding further support to the observation that the waves broke close to shore and surged up the beach face. Additional support for this is the narrow width of the surf zones present which indicates a relatively steep nearshore and results in a lack of significant wave dissipation. This in turn, correlates with a reflective system where wave energy is reflected from the shoreline and this reflection was often visually observed.

Wave period depended on local wave conditions at that time and appeared similar at all the beaches studied on the same day. Because of the close vicinity, there would be no significant change in wave period between beaches at one time. Wave period ranged between 7.9 and 11.0 seconds.

### 3.3.2 Sediment characteristics

It has been noted that there are significant textual variations between beach cusp horns and embayments (Komar, 1973; Antia, 1987). A textual analysis was undertaken to investigate the nature of the sediment characteristics of the cusp horns and embayments at each of the investigation sites (Table 3.2). The analysis was undertaken using the R.S.A which calculates the textual properties in terms of a hydraulic grain size based on the fall velocity.

Table 3.2. Textual characteristics of sediment samples analysed using the Rapid Sediment Analyser.

Samples marked \* were too coarse to be put through the R.S.A and have been sieved by hand.

Beach	Position on profile	Mean sediment size ( $\phi$ )(mm)	Sorting (So) (mm)	Skewness (Sk)
Buffalo 3/91	Horn*	6.00	0.85	0.42
	Embayment	0.50	0.88	0.02
Buffalo 4/91	Horn*	8.00	0.88	0.40
	Embayment	0.32	0.90	0.09
Buffalo 7/92	Horn*	9.00	0.97	0.44
	Embayment	0.50	1.27	-0.03
Cooks 5/92	Horn	0.32	0.62	0.12
	Embayment	0.29	0.61	-0.02
Hahei 5/92	Horn	0.41	0.44	0.12
	Embayment	0.35	0.45	0.22
Hahei 8/92	Horn	0.48	0.41	0.18
	Embayment	0.32	0.46	0.25
Kuaotunu 3/91	Horn*	20.00	0.51	0.96
	Embayment	0.32	0.37	0.15
Maramaratotara 3/92	Horn	0.57	0.72	0.30
	Embayment	0.46	0.63	0.28
Maramaratotara 5/92	Horn	0.64	0.67	0.08
	Embayment	0.45	0.61	0.29
Maramaratotara 7/92	Horn	0.65	0.60	0.38
	Embayment	0.46	0.66	0.14
Maramaratotara 8/92	Horn	0.50	0.65	0.31
	Embayment	0.38	0.62	0.14
Rings 3/91	Horn	0.50	0.60	0.16
	Embayment	0.48	0.63	0.20
Rings 3/92	Horn	0.72	0.56	0.14
	Embayment	0.43	0.52	0.16
Rings 5/92	Horn	0.57	0.59	0.18
	Embayment	0.46	0.51	0.30
Rings 8/92	Horn	0.52	0.58	0.19
	Embayment	0.40	0.60	0.20
Wharekaho 5/92	Horn	0.42	0.49	0.18
	Embayment	0.38	0.46	0.34
Wharekaho 7/92	Horn	0.42	0.48	0.25
	Embayment	0.41	0.42	0.30

### *Grain size*

All embayment sediment samples were of medium sand except for Buffalo Beach (4/91 and 7/92) (Fig. 3.3) and Rings Beach (5/92) which were classified as coarse sand (see Appendix A for textual classifications). There was some variation in the mean grain size between the medium sand beaches, Rings and Maramaratotara being the next coarsest, Wharekaho, Hahei and Kuaotunu being less coarse and Cooks the finest.

For the horn samples, Kuaotunu and Buffalo had pebble size sediment. Rings and Maramaratotara consisted of coarse sand while Wharekaho, Hahei and Cooks Beaches were medium sand. Invariably, the cusp horns are coarser than the cusp embayments (Fig. 3.4).

### *Sorting*

Wharekaho, Hahei and Kuaotunu all have well sorted embayment sediments. Rings, Maramaratotara and Cooks Beaches are moderately well sorted and Buffalo Beach sediments are poorly sorted.

The degree of sorting also varies in the horn samples where Hahei and Wharekaho, Maramaratotara and Hahei are well sorted; Rings, Cooks and Kuaotunu and Cooks are moderately well sorted; and Buffalo Beach is moderately sorted.

This correlates well with the difference in relative wave energy between beaches. Those beaches that are exposed to higher wave energy, e.g. Wharekaho Beach, are better sorted than those exposed to lower wave energy, e.g. Buffalo Beach, which are more poorly sorted.

There is little variation in sorting between the embayment and horn sediments but, generally, the horn sediment is better sorted than the embayment sediment except for Buffalo Beach.

### *Skewness*

All beaches exhibit finely skewed sediment in the embayments, except for Cooks Beach and Buffalo Beach which are near symmetrical.



Fig. 3.3 Shell sediment characteristic of the apex of cusp horns at Buffalo Beach.



Fig. 3.4 Beach cusps at Kuaotunu Beach showing the difference in sediment size between the cusp horn (20.00 mm) and the cusp embayment (0.32 mm).

The horn samples show a similar trend where Rings, Wharekaho and Hahei are finely skewed. Maramaratotara Beach is more variable over time ranging from near symmetrical to very finely skewed. Kuaotunu and Buffalo Beaches are both very finely skewed.

There is little variation between the skewness of the horn and embayment sediment except for Buffalo Beach where the horn sediment is more finely skewed than the embayment sediment.

### 3.3.3 Cusp morphology characteristics

Table 3.3 presents the data collected regarding cusp morphology. Beach cusps are least common on Buffalo, Kuaotunu and Cooks Beaches. The cusps on these beaches have a low elevation and seldom become well developed. In contrast Maramaratotara, Hahei, Rings and Wharekaho Beaches consistently exhibit cusps.

Table. 3.3 Average cusp morphological data describing the dimensional and spatial distribution of beach cusps for each observational period.

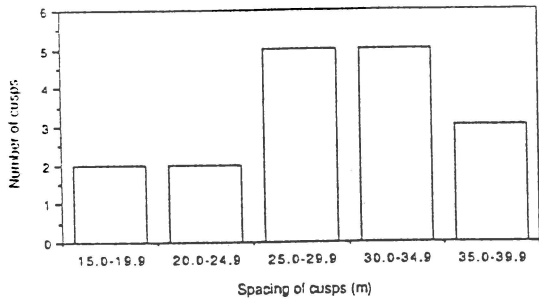
Beach	Date	$\lambda_c$	$\%v\lambda$	$\lambda_e$	$\beta_m$	$\beta_h$	$\beta_e$	$\% \lambda$	levels
Buffalo	3/91	20.30	-	0.39	3.70	6.50	3.50	0.5	1
Buffalo	4/91	10.26	53.70	0.25	3.00	7.5	2.90	1.0	1
Buffalo	7/92	8.08	40.84	0.26	2.50	9.0	3.4	1.0	1
Cooks	5/92	21.07	9.87	0.33	3.00	4.80	1.94	30.0	1
Hahei	5/92	30.05	22.92	0.51	5.50	5.71	3.80	65.0	1
Hahei	8/92	26.74	12.04	0.42	5.80	6.0	3.20	70.0	2
Kuaotunu	3/91	13.52	21.80	0.42	3.00	8.00	2.80	100.0	1
Maramaratotara	3/92	28.20	21.34	0.50	6.00	6.60	3.2	70.0	1
Maramaratotara	5/92	28.36	9.16	0.50	5.20	5.80	4.76	80.0	1
Maramaratotara	7/92	25.91	19.14	0.52	6.00	7.10	3.30	100.0	2
Maramaratotara	8/92	21.27	24.90	0.50	5.60	5.80	4.20	100.0	2
Rings	3/91	30.61	10.60	0.50	5.50	6.60	4.50	80.0	1
Rings	3/92	29.69	9.16	0.50	5.50	5.20	4.2	55.0	1
Rings	5/92	30.46	6.56	0.48	5.70	7.90	5.71	50.0	1
Rings	8/92	25.17	11.30	0.45	5.50	6.20	4.80	60.0	2
Wharekaho	5/92	30.55	15.41	0.68	7.00	10.00	4.50	30.0	1
Wharekaho	7/92	33.31	11.80	0.70	7.60	9.00	4.80	60.0	2

The percentage of a beach that is cusped varies and appears to be dependant on swell direction, local sheltering, wave refraction and beach length. Buffalo and Cooks Beaches had the least percentage of the beach cusped and were the longest beaches investigated. The shorter beaches (Maramaratotara and Rings) had a greater proportion of their length cusped. Generally, the straighter beaches had a greater percentage of their length cusped (50-100%) whilst the more curved beaches had less of their length cusped (0.5-30%).

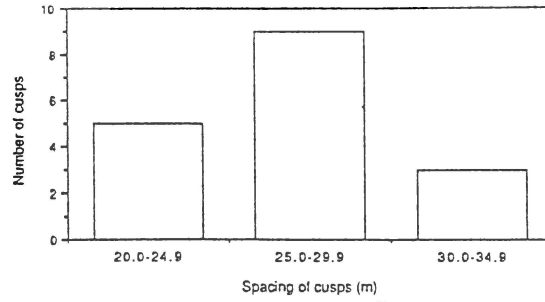
The regularity of cusp spacing is illustrated in the histograms of Figure 3.5. Rings Beach had the most regularly spaced cusps with a variation from the mean spacing of between 6.56-11.30%. Buffalo Beach had the most variability in terms of cusp spacing, having a variation of between 40.0-53.0%. Maramaratotara also displayed less regular cusps, the variation from the mean ranging from 9.16 to 24.9%. The other beaches ranged between 9.87% to 22.92%.

Subaerial beach slope ranges from 2.0-8.0°. Wharekaho is the steepest beach (7.0-8.0°); Rings (5.5-6.0°), Maramaratotara (5.0-6.0°) and Hahei (5.5-6.0°) have intermediate beach slopes while Buffalo (2.5-4.0°), Cooks (3.0°) and Kuaotunu (3.0°) have the lower slopes.

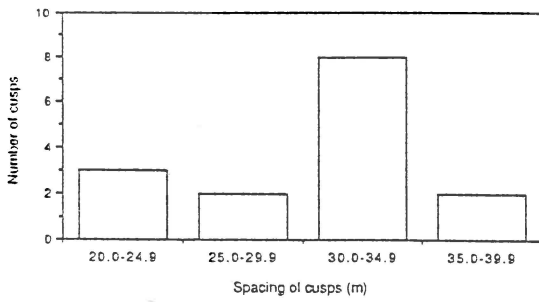
Profiles through representative cusp horns and embayments differed from beach to beach. Profiles are illustrated in Figure 3.6.



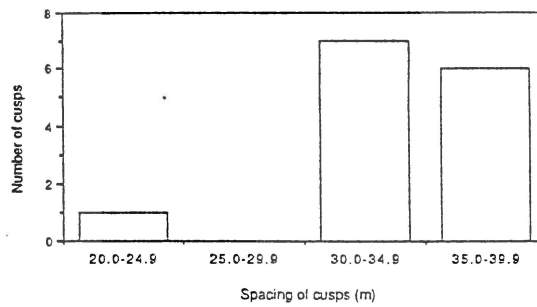
Hahei Beach 5/92



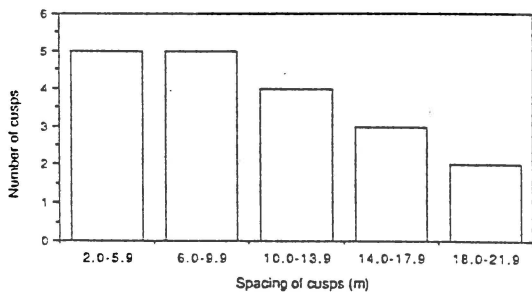
Hahei Beach 8/92



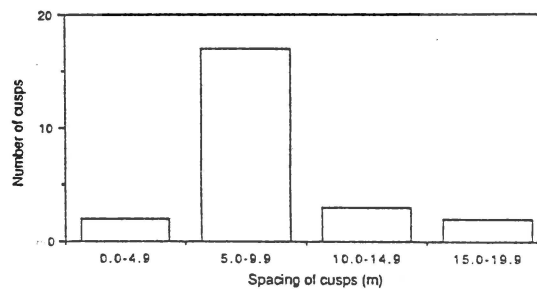
Wharekaho Beach 5/92



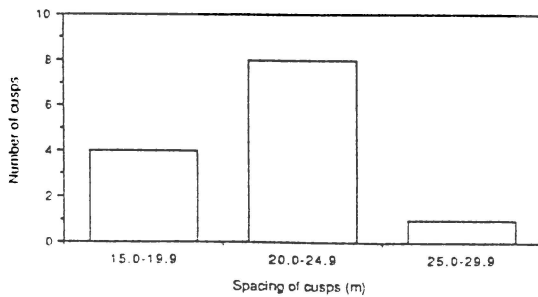
Wharekaho Beach 7/92



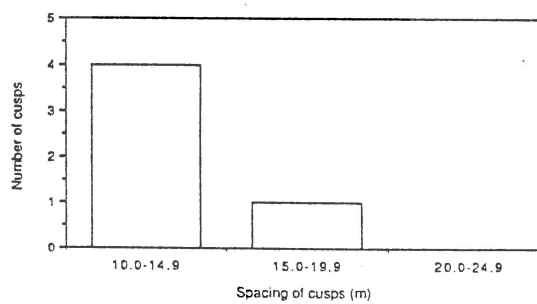
Buffalo Beach 4/91



Buffalo Beach 7/92

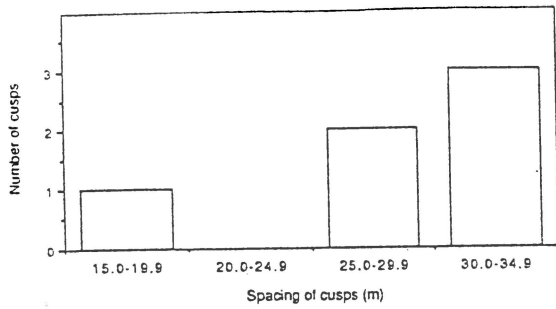


Cooks Beach 5/92

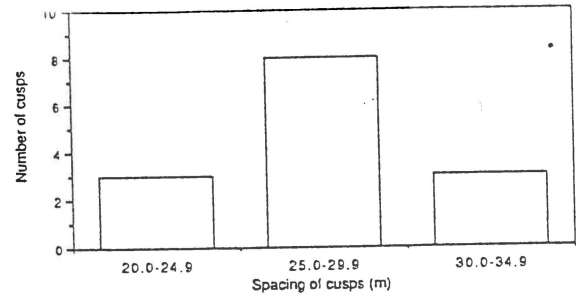


Kuaotunu Beach 3/91

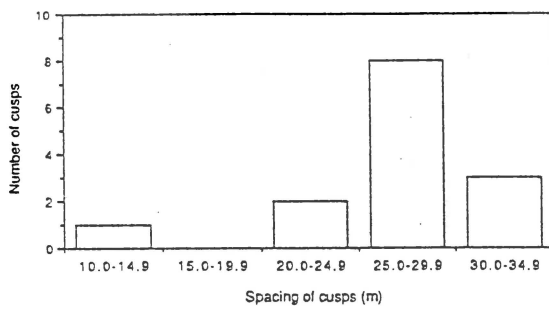
Fig. 3.5 Histograms of cusp spacing for each observation period of eastern Coromandel beaches



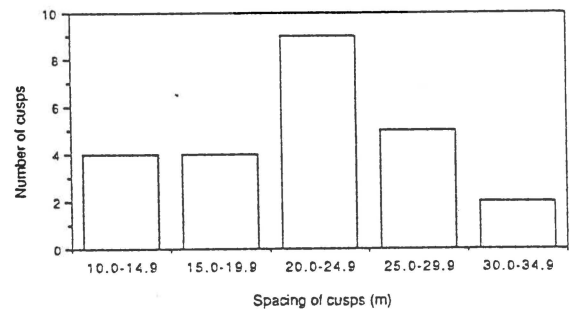
Maramaratotara Beach 5/92



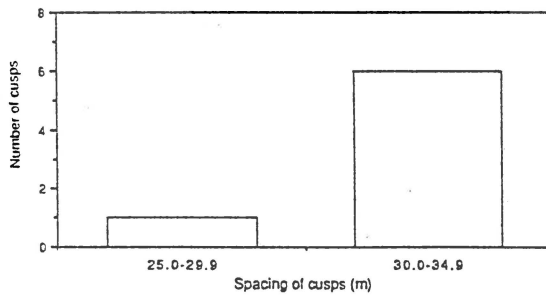
Maramaratotara Beach 3/92



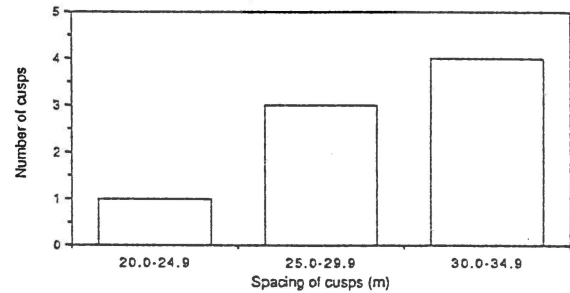
Maramaratotara Beach 7/92



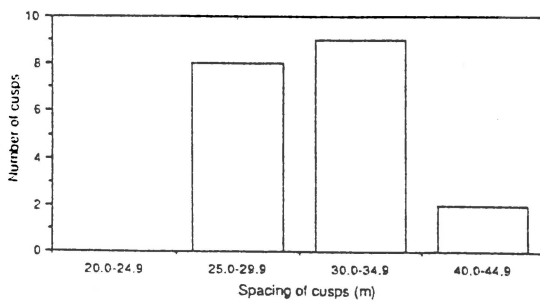
Maramaratotara Beach 8/92



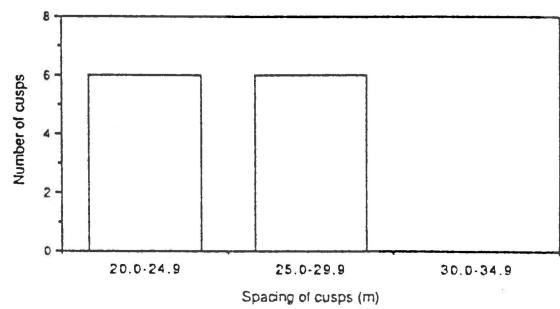
Rings Beach 3/91



Rings Beach 3/92



Rings Beach 5/92



Rings Beach 8/92

Fig. 3.5 Histograms of cusp spacing for each observation period of eastern Coromandel beaches

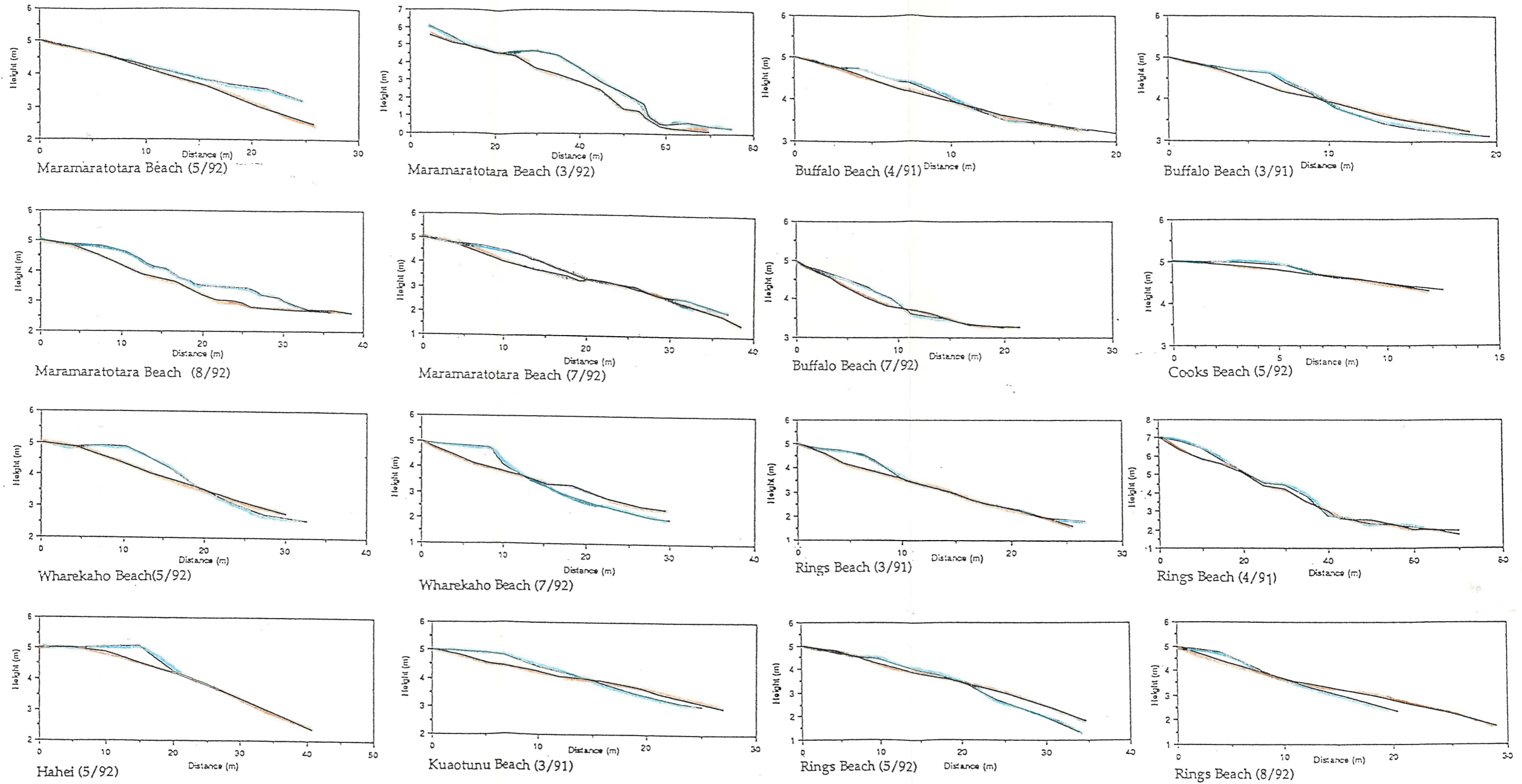
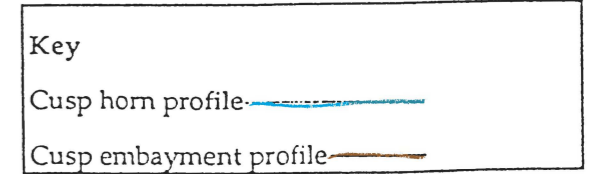


Fig. 3.6 Profiles of representative cusp horns and cusp embayments at each observation period of cusped beaches on the eastern Coromandel.  
(The apex of the cusp horn corresponds to the high tide mark).



### 3.4 Cusp changes over time

There is a vast amount of published data regarding observations of beach cusps. Many studies observe beach cusps after their formation and attempt to relate cusp morphology to the conditions present at that time even though the conditions that caused the formation of the cusps may have been very different. It is therefore useful to collect time series data to determine the values of the parameters thought to form the cusps at the time of initiation.

Breaking wave height, wave period, cusp development, wind speed and directional data were collected by local residents at two of the beaches (Rings and Maramaratotara) and are analysed in this section. Breaking wave height and wave period were determined visually whilst wind direction and speed, and cusp development were estimated qualitatively. Cusp development was assessed using a rating scheme of between 0 (no cusps) and 4 (well developed cusps). Wind speed was also rated between 0 (indicating no wind) and 4 (a gale).

#### 3.4.1 Maramaratotara Beach

Maramaratotara Beach was monitored by a local resident for a period of ten weeks (1/6-18/8/92) to investigate beach morphology changes over time in relationship to environmental changes. The resultant plots (Fig. 3.7) show the variation in the five recorded parameters over time and these data can be analysed to determine any trends.

Two sets of cusps existed during this time. The set further up the beach appeared very stable and did not change during the investigated period. The younger, more closely spaced set was more changeable and Fig. 3.7 illustrates changes to this set of cusps.

In early June, the swell was from the east and had a long period of 15.0 s. There was little wind and conditions were calm. The cusps were well developed but were destroyed when the breaking wave height rose over 2.0 m (Fig 3.7 A).

The wind swung around to the west, south-west in mid June and the cusps reformed as energy decreased. Cusp development reached a maximum when there was a strong southeasterly wind and there was a 1.5 m breaking wave height. Cusp development ceased as the wind swung around to the northwest and the swell size decreased (Fig 3.7 B).

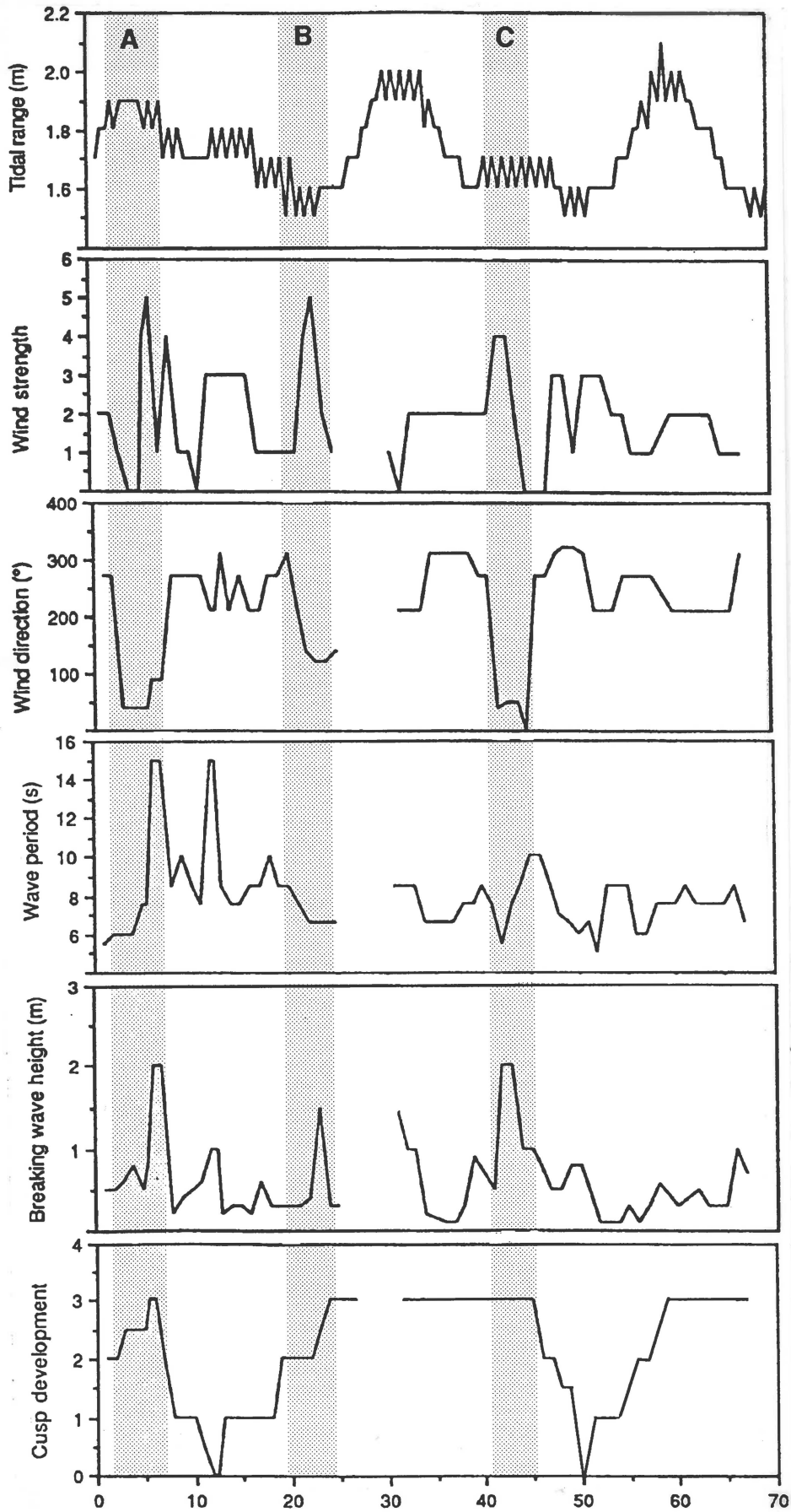


Fig. 3.7 Time series plots of data gathered at Maramaratotara Beach 1/6 - 14/8/92 (the shaded areas correspond to periods of change discussed in the text).

An easterly, with 2.0 m breaking waves, accompanied by shorter wave periods and strong winds, destroyed the cusps (Fig 3.7 C). The cusps reformed when the wave period (5.0-8.0 s) and wave height (0.2-1.0 m) were variable (Fig. 3.8).



Fig. 3.8 Beach cusps on Maramaratotara Beach at the end of the observation period. Note the very calm conditions, the lack of sea waves and very small swell waves. The cusps present remained as shown in this photo for several days because of the lack of onshore swell that may alter or destroy them.

Of interest here is the correlation between cusp development and tidal height. The cusps were destroyed by larger waves from the east and reformed as the tidal height became larger. The highest tides correspond to maximum cusp development.

#### 3.4.2 Rings Beach

Rings Beach was monitored for a period of 4 weeks. Fig. 3.9 illustrates the results collected during this period. Two sets of cusps were observed during this time, the set A located higher on the beach and having a mean spacing of 24.0 m, while the lower more changeable set B having a mean spacing of 14.0 m.

At the start of the record, only the larger set of cusps existed. Breaking wave heights were around 1.0 m and the wind was onshore (northerly). The set B cusps formed on the eastern end of Rings Beach at the end of this northerly as wave energy decreased (Fig. 3.9 A).

Both sets of cusps maintained their form as conditions became calmer with offshore winds and little swell. Set B cusps were destroyed by a northwesterly change when the breaking wave height was 1.0 m and the wave period was long (Fig. 3.9 B). Set A cusps at the western end of the beach were also destroyed, the cusps at the eastern end remaining. Conditions then calmed and the cusps remained unchanged.

The smaller cusps appeared again as the wind swung around to the northwest (Fig. 3.9 C), conditions were choppy and the lower level set B cusps were destroyed in 24 hours (Fig. 3.9 D). A northeasterly change, accompanied by 2.0 m long period swell, destroyed the smaller cusps and new larger cusps (A) appeared higher on the beach face (Fig 3.9 E), replacing the original set A. Conditions became calmer and the cusps stabilised.

### 3.5 Cusp formation and development

Cusp formation appears to be the result of reworking and sorting of sediment on the beach face. On two occasions, cusp formation was observed to take place on Buffalo Beach providing the opportunity to document the processes involved in cusp development.

#### 3.5.1 Buffalo Beach (3/91).

Formation of beach cusps was observed during a two day period in late March 1991.

On 29 March, the beach was devoid of cusps apart from some slight cusp development, of two thin, long, rectangular shell deposits of negligible elevation, under the adjacent rip rap seawall (Fig. 3.10).

On 30 March, three cusps had formed at this location and these were more pronounced than those observed the previous day (Fig. 3.11). The wave height was measured as 0.7 m and the wave period as 9.5 s.

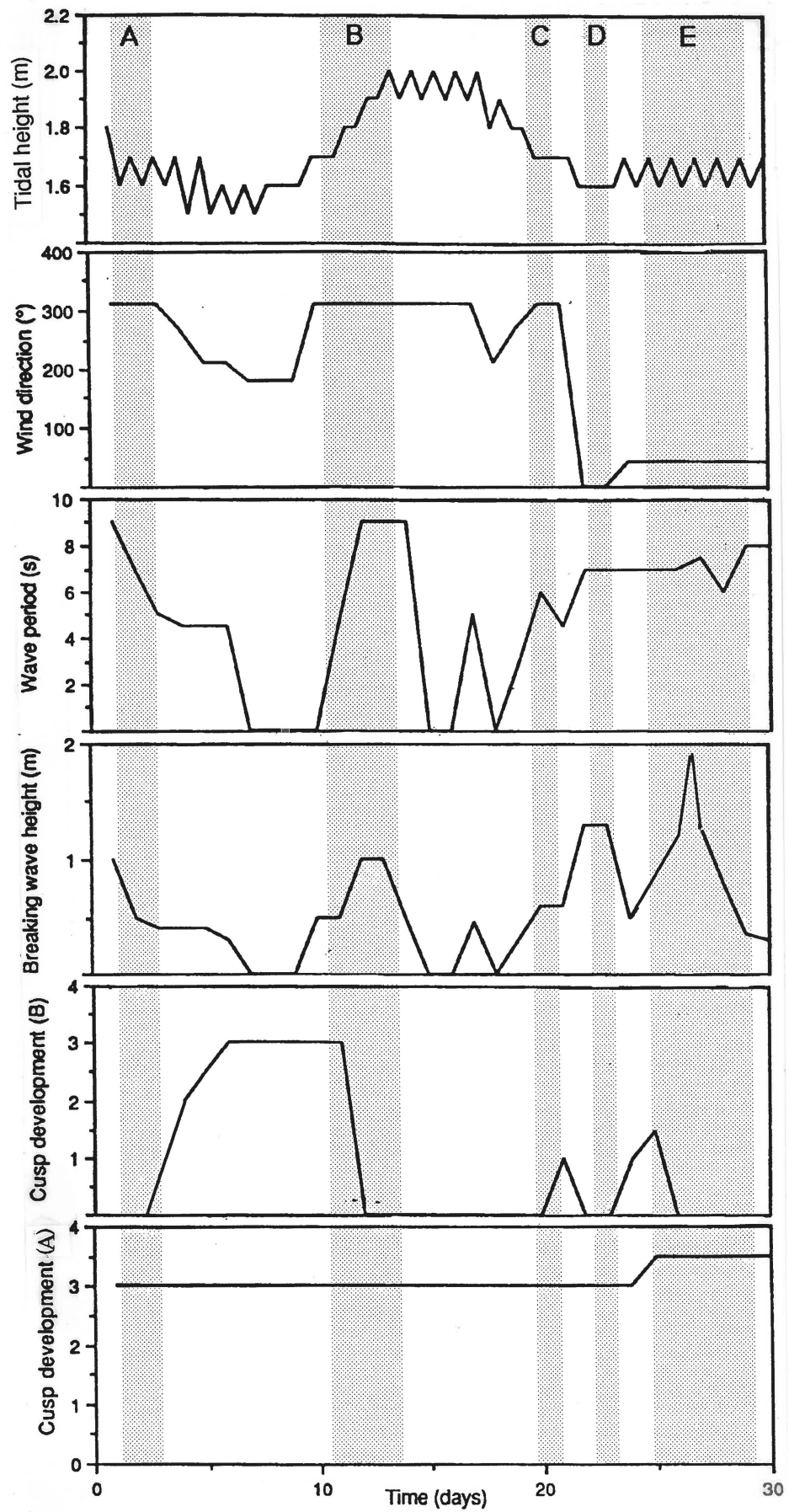


Fig. 3.9 Time series plots of data gathered at Rings Beach 17/6 - 17/7/92 (The shaded zones corresponded to periods of change discussed in the text).

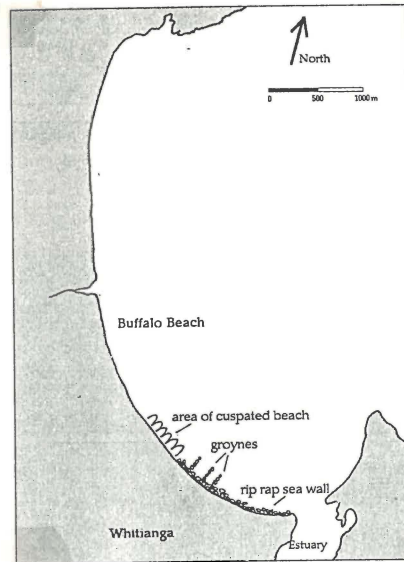


Figure 3.10 Spatial distribution of beach cusps on Buffalo Beach (3/91)

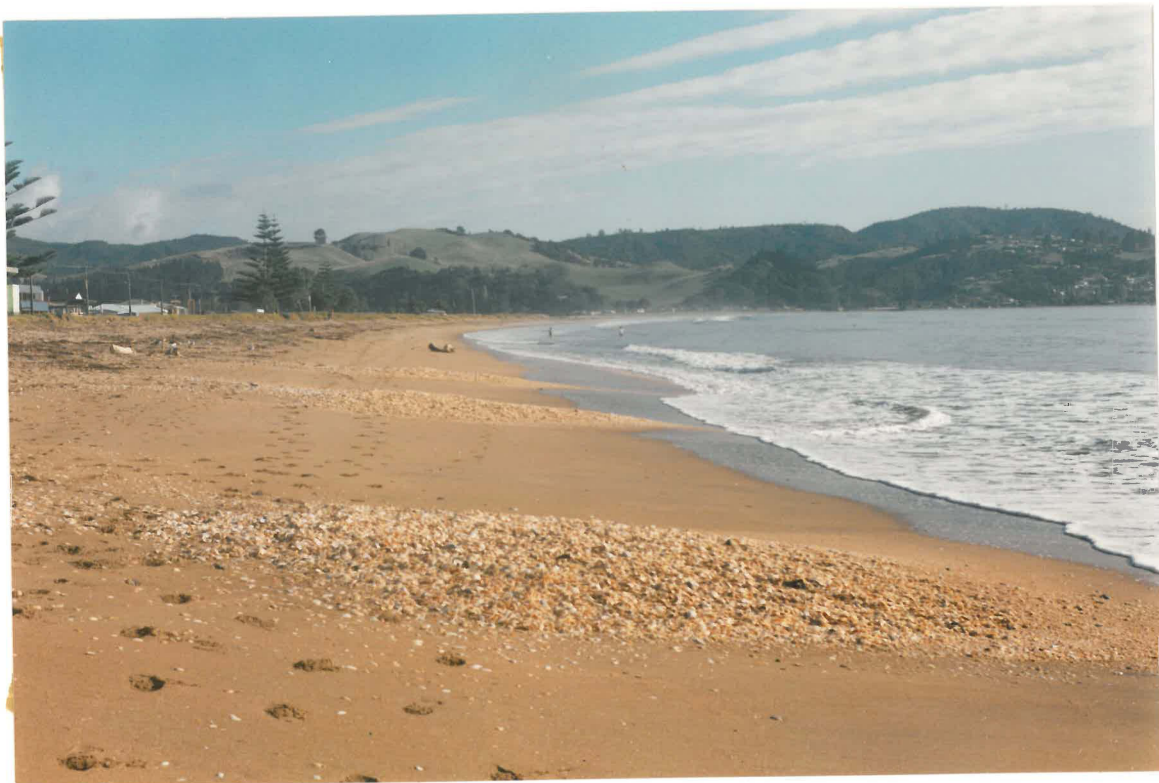


Fig. 3.11 Cusps at Buffalo Beach during formation. The cusps (composed of shell material) (6.00 mm) are deposited on a finer (0.5 mm) beach face. Note the clam conditions, the narrow surf zone and the swash surging up the beach face. The breaking wave height was around 0.5 m.

Later in the day, 1 hour after high tide, the cusps were active showing the characteristic circulation patterns (described in section 3.6). The shape of the cusps changed over time, becoming increasingly pronounced. The cusps appeared to be spreading laterally, becoming

more 'shark-tooth' shaped. The largest shell material accumulated on the highest point of the horn. Smaller shell material was moved to the side of the horn by the lateral movement of the swash (Fig. 3.12). Hollows consisting of coarse material were evident at the base of each horn while a delta of finer sediment was observed offshore from each embayment (see 3.6 for more detail regarding the origin of these hollows).

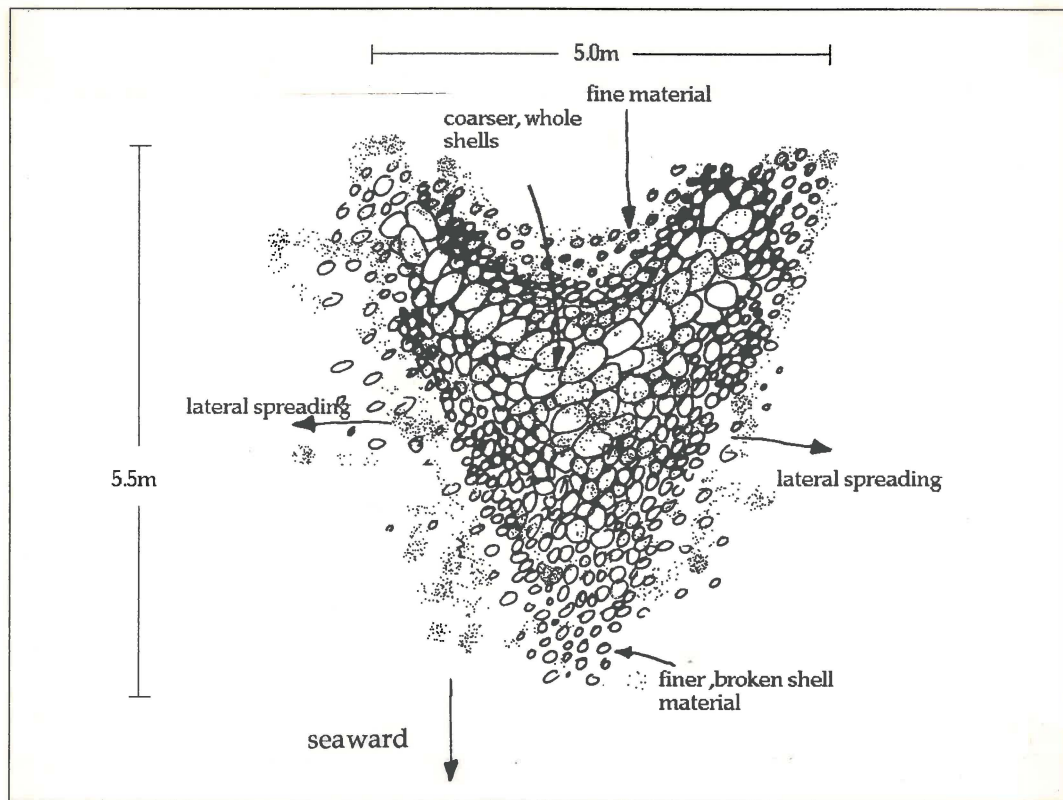


Figure 3.12 Sediment size distribution on the developing cusp horn at Buffalo Beach (3/91). The coarsest sediment was deposited at the top and apex of the cusp horn, while smaller, broken shell material was pushed by the action of swash, over the back of the horn or to the sides resulting in a widening of the cusped shape.

It was also noted that three new cusps were developing to the north of the existing cusps. These cusps formed in two hours, either side of high tide. To the south of the first three cusps, three more cusps were forming, these being the least developed of the nine. The sediment of these final three accumulated in the swash zone and existed as thin, elongated deposits similar to the beginnings of the first three cusps viewed 24 hours earlier.

### 3.5.2 Buffalo Beach (4/91).

Beach cusps were observed to form and be destroyed during a two day investigation at Buffalo Beach (Figure 3.13). On the 28 April, 25 cusps were observed, the first occurring at the end of the rip rap sea wall. These cusps were irregularly spaced (the smallest 3.5 m, the largest 21.9 m apart). The variation in the spacing seemed indicative of a transitional stage where the beach was adjusting to a change in environmental conditions as wave energy decreased. They also varied in the degree of their development (in terms of cusp elevation), the more developed cusps nearest the seawall.



Fig. 3.13 Beach cusps on Buffalo Beach during a two day observation period. Note small elevation between the cusp horn and embayment. The cusps were partially destroyed on the next high tide.

On the 28 April, the wave period ( $T_j$ ) was 11 seconds and the breaking wave height ( $H_b$ ) averaged 0.3 m. Wave groupiness was evident. The waves approached parallel to the shore and were very long crested. The waves were surging to plunging in nature.

At 6pm, as the cusps became active on the rising tide, the cusps were partially destroyed by wave action. The wave height increased to 0.7 m and conditions became less choppy.

The hollows present at the base of the cusp horns persisted even when cusp horn sediment was removed from the beach face. The position of one of these hollows was marked by two pegs on the beach face and a cusp formed on the beach face directly up from this monitored hollow suggesting that the hollows are a precursor to cusp formation.

The nature of the cusps was continually changing at high tide in terms of the cusp shape and elevation, some being destroyed and others partially reforming.

On 29 April conditions had deteriorated with squalls coming off the sea. The wind was still onshore and there was a range of wave periods. The large waves still had a period of 11 seconds but the smaller wind forced waves had a period of five seconds. The breaking wave height was 0.8-1.0 m.

All the cusps on the beach had been destroyed over night apart from the largest, most well developed cusps under the rip rap wall, with only three remaining.

### **3.6 Cusp sediment movement and swash circulation**

Swash circulation patterns, resulting in erosion and accretion of the beach face, in the process of cusp formation has been well documented in the literature (Sallenger, 1979; Dean and Mauremeyer, 1981) (Fig. 3.14). Observations on the eastern Coromandel support these previous investigations. The cusps form in the swash zone and it is the action of the swash that forms the cusp topography. When an incoming wave breaks in the breaker zone, it propagates over the beach face as swash. The wave breaks evenly up over the step and surges onto the cusp horns. In this process, there is a diminution of velocity due to the slope of the beach face, the foreshore roughness, flow depth and momentum. This transforms the flow from turbulent to laminar as the swash reaches the extent of the upward motion.

The sediment carried by the turbulent flow is rapidly deposited on the horn when this transition takes place due to percolation into the coarser sediment of the horn. Because of the more permeable nature of the horn, water is added to the groundwater discharge causing liquifaction at the base of the horn where the groundwater reaches the surface (Fig. 3.15).

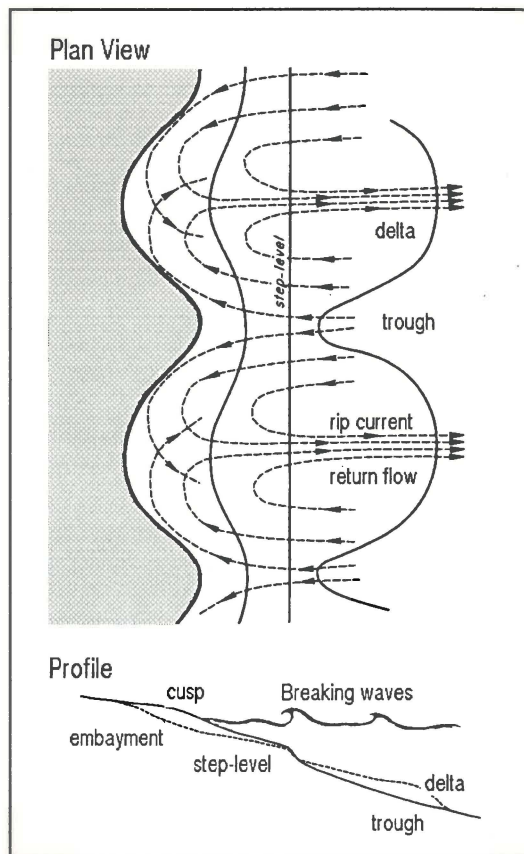


Fig. 3.14 Circulation of swash over a cusped topography (Komar, 1976).



Fig 3.15 Liquifaction ,due to discharge of groundwater, producing a hollow at the base of each cusp horn at Buffalo Beach.



Fig. 3.16 Incoming swash flowing over the cusp horn , entraining sediment from the liquified material in the hollow at the base of the cusp and moving it up onto the cusp where it will be deposited as the swash loses energy due to friction and percolation (Kuaotunu Beach).



Fig. 3.1 Wave breaking on cusped topography at Maramaratotara Beach. Note how the breaking wave is retarded from flowing into the embayment because of the return flow through the embayments and note how the swash is about to flow onto the horns unimpeded because there is little return flow from the horns because of the lateral movement of the swash into the adjacent embayments

This results in a hollow at the base of each horn where material is easily entrained and transported by the next incoming swash, and deposited on the horn (Figure 3.16).

The remaining swash is divided by the horn into two divergent streams and each flows into the adjacent embayment. The two converge into the centre of the embayment and form the backwash which flows seaward at a greater intensity than the previous swash run up. To begin with the velocity of the backwash is low and the flow is laminar but this changes to turbulent flow and sediment can be transported seaward. The addition of groundwater at the surface to the backwash increases the backwash volume, propelling the finer grains up into the turbulent flow. The sediment is moved offshore where it is deposited to form a delta opposite each bay.

Because the return flow through the embayment has a higher velocity than the next incoming breaking wave, the swash is retarded from flowing into the embayment (Fig. 3.17) and so is concentrated onto the cusp horn and so a circulation pattern is established. This characteristic circulation was observed on all beaches throughout the investigation when cusps were present.

### **3.7 Statistical analysis**

Associations between the variables were identified quantitatively using statistical analysis, namely with Pearson Product-Moment correlation, linear regression and principle components analysis. The objective of the analysis was to investigate the interrelationships between the variables measured, in particular, which parameters are associated with the development of beach cusps.

#### **3.7.1 The data sets**

Statistical analysis was undertaken on two data sets. The first (Data set A) involved parameters that were measured at all beaches, resulting in 20 variables from 17 cases at 7 beaches . The variables measured are tabulated in Table 3.4.

Table 3.4 Variables used for the principle component analysis for data set A (those variables marked \* were only used in the correlation analysis and not the principle components analysis).

Variable Description	abbreviation	Units
Wave height at breaking	$H_b$	m
Wave period	$T_i$	s
Wave steepness at breaking	$H_b/L_s$	-
Wave type	WT	-
Water depth at breaking*	$h_b$	m
Mean particle size (embayment sediment)	$\phi_e$	mm
Mean particle size (horn sediment)	$\phi_h$	mm
Sorting (embayment sediment)	$So_e$	mm
Sorting (horn sediment)	$So_h$	mm
Skewness (embayment sediment)	$Sk_e$	-
Skewness (horn sediment)	$Sk_h$	-
Horn gradient	$\beta_h$	°
Embayment gradient	$\beta_e$	°
Beach gradient	$\beta_m$	°
Surf zone width	$\chi_s$	m
Cusp spacing	$\lambda$	m
Cusp elevation	$\lambda_e$	m
% variation from cusp spacing mean	$\% \lambda$	%
Tidal Height *	TH	m
Swash excursion	Se	m
Exposure	Exp	-

Table 3.5 Variables used for the principle components analysis for Data set B (all variables were analysed using both principle components and the correlation analysis).

Variable description	Abbreviation	Units
Wave height at breaking	$H_b$	m
Wave period	$T_i$	s
Cusp development	$\lambda$	-
Wind direction	W D	°
Wind strength	W S	-
Tidal Height	TH	m

The second analysis was performed on the time series data (Data set B) from Maramaratotara Beach (discussed in section 3.4), consisting of 7 variables for 68 cases. These variables are shown in Table 3.5. The two sets of data were used because for data set A, the variables were measured after cusp formation and may not be indicative of the conditions that form cusps. Data set B measures cusp changes over time.

### 3.7.2 Pearson Product-Moment correlation

Tables 3.6 and 3.7 show correlation matrices of the results of the Pearson Product-Moment correlation analysis. This was undertaken to assess the correlation between pairs of variables. The correlation measures the degree of linear association. Preliminary regression plots of the variables showed that the relationships were linear so this method was considered to be the most appropriate. The correlation matrices can be used in conjunction with factor matrices from a principle components analysis.

### 3.7.3 Principle components analysis

To identify the general interactions between the variables measured in terms of cusp morphology, an R mode principle components analysis was performed on a data matrix. The analysis was achieved using Data Desk® available on the Apple™ computer system at the University of Waikato. Principle components analysis involves the analysis of a matrix of correlations between data variables and yields a number of factors, comprising of variables which account for the variance of that factor. The greater the variance accounted for by the factor, the more influential it is. Within each factor, each variable is given a factor loading which is an indicator of the significance of that variable. Each factor is independent of the other factors.

### 3.7.4 Factor Analysis results

#### *Data set A*

The resultant factor matrix for Data set A is shown in Table 3.8. Five factors were retained that explain 90.4% of the variation within the data set.

Table 3.6 Correlation matrix using the Pearson Product-Moment correlation analysis for data set A.

	$\omega$	Se	hb	SSP	% $\lambda$	TH	Exp	$\beta_e$	So e	$\beta_h$	Sk h	$\lambda$	Sk e	So h
$\omega$	1.00													
Se	-0.517	1.00												
hb	0.056	0.045	1.00											
SSP	-0.290		0.373	1.00										
% $\lambda$	-0.056	-0.466	-0.099	0.454	1.00									
TH	-0.337	-0.224	-0.247	0.020	0.113	1.00								
Exp	0.060	0.603	-0.017	-0.678	-0.337	-0.275	1.00							
$\beta_e$	0.512	0.544	0.030	-0.324	-0.357	-0.080	0.389	1.00						
So e	0.285	0.618	0.234	0.853	0.517	0.080	-0.748	-0.214	1.00					
$\beta_h$	0.084	0.388	0.252	0.295	0.292	0.002	0.109	0.263	0.141	1.00				
Sk h	0.343	0.668	-0.109	-0.674	-0.231	-0.261	0.821	0.515	-0.638	0.223	1.00			
$\lambda$	0.181	0.688	0.093	-0.729	-0.692	-0.382	0.752	0.567	-0.679	-0.139	0.688	1.00		
Sk e	0.320	-0.284	-0.046	0.337	0.362	0.334	-0.293	-0.404	0.139	0.369	-0.268	-0.657	1.00	
So h	0.496	-0.611	0.153	0.720	0.490	0.045	-0.769	-0.213	0.930	0.112	-0.560	-0.684	0.230	1.00
$\phi_h$	0.728	-0.382	-0.052	0.455	0.415	0.349	-0.464	-0.405	0.221	0.334	-0.356	-0.750	0.925	0.300
$\phi_e$	0.811	-0.047	0.427	0.327	-0.066	-0.218	-0.259	-0.470	0.539	0.215	-0.056	0.051	-0.086	0.553
$\lambda_e$	0.203	0.729	0.162	-0.628	-0.489	-0.302	0.887	0.564	-0.674	0.264	0.761	0.824	-0.296	-0.660
$\chi_s$	0.144	0.731	0.136	-0.643	-0.329	-0.288	0.920	0.530	-0.666	0.229	0.781	0.825	-0.367	-0.724
Ti	0.059	-0.057	-0.404	-0.282	0.019	0.025	-0.268	-0.124	-0.179	-0.230	0.048	-0.064	0.080	0.010
Hb	0.056	-0.042	1.00	0.370	-0.107	-0.245	-0.018	0.032	0.229	0.248	-0.111	0.096	-0.046	0.149
Hb/Ls	-0.000	0.054	0.773	0.488	0.113	-0.446	-0.000	0.022	0.339	0.328	-0.144	0.026	-0.176	0.190
WT	-0.323	-0.559	0.476	0.970	0.416	0.056	-0.711	-0.429	0.794	0.236	-0.730	-0.738	0.373	0.685
$\beta_m$	0.251	0.749	0.117	-0.675	-0.433	-0.290	0.875	0.608	-0.602	0.133	0.773	0.880	-0.495	-0.632

Correlation for data set A continued.

	$\phi_h$	$\phi_e$	$\lambda_e$	$\chi_s$	Ti	Hb	Hb/Ls	WT	$\beta_m$
$\omega$									
Se									
hb									
SSP									
% $\lambda$									
TH									
Exp									
$\beta_e$									
So e									
$\beta_h$									
Sk h									
$\lambda$									
Sk e									
So h									
$\phi_h$	1.00								
$\phi_e$	-0.104	1.00							
$\lambda_e$	-0.463	0.015	1.00						
$\chi_s$	-0.534	-0.038	-0.910	1.00					
Ti	0.278	-0.097	-0.212	-0.276	1.00				
Hb	-0.051	0.427	0.161	0.135	-0.400	1.00			
Hb/Ls	-0.213	0.297	0.051	0.147	-0.677	0.771	1.00		
WT	0.500	0.255	-0.659	-0.671	-0.235	0.474	0.514	1.00	
$\beta_m$	-0.681	0.058	0.910	0.952	-0.316	0.117	0.138	-0.722	1.00

Table 3.7 Correlation matrix using the Pearson Product-Moment correlation analysis for data set B.

	T <sub>i</sub>	H <sub>b</sub>	$\lambda_d$	W D	W S	TH
T <sub>i</sub>	1.00					
H <sub>b</sub>	0.410	1.00				
$\lambda_d$	-0.245	0.324	1.00			
W D	-0.139	-0.515	-0.342	1.00		
W S	0.060	0.216	-0.064	-0.117	1.00	
TH	0.080	-0.055	-0.255	-0.175	-0.070	1.00

Factor I (accounting for 48.6 % of the variance) may be identified as a sediment characteristic factor that groups the sediment variables with the subaerial beach slope ( $\beta_m$ ), surf zone width ( $\chi_s$ ) and cusp characteristics (cusp spacing ( $\lambda$ ), variation from the mean ( $\% \lambda$ ), and cusp elevation ( $\lambda_e$ )). It also suggests that beach sediment characteristics are associated with beach exposure ( $E_{xp}$ ) and the wave type (WT). This, in turn, suggests that as the slope of the beach increases, the cusps become better developed (in terms of the vertical height between the cusp horn and embayment), the horns are spaced further apart and the cusps are more regular in their spacing. As the subaerial beach slope increases, the waves become more surging in nature and the surf zone decreases in width.

Factor II (explaining 15.8 % of the variance) groups wave period ( $T_i$ ) with the wave height at breaking ( $H_b$ ) and wave steepness (WS). The variables have a negative loading, except for wave period suggesting that as wave period decreases, wave height and wave steepness increase (eg. storm conditions). No association is indicated between the wave characteristics and the cusp characteristics. The sorting ( $S_o$ ) and mean grain size ( $\phi$ ) of the cusp horns are also included in this factor suggesting that as the grain size of the horns increase, so does the degree of sorting of that sediment.

Factor III (accounting for 12.2 % of the variance) relates the mean sediment size and slope of the cusp horns ( $\beta_h$ ) suggesting that as sediment size increases, so does the horn gradient. Also included within the factor is the skewness of the embayment sediment ( $Sk_e$ ). The grouping suggests that on a beach of steep slope and large grain size of the cusp horns are associated with a positive skewness.

Factor IV groups wave period by itself and suggests that this parameter is independent of the other variables, accounting for 7.8% of the variance in the data set.

Factor V (explaining 6.0 % of the variance) groups the percentage variation from the cusp spacing mean ( $\% \lambda$ ) with the breaking wave height implying that larger waves may be associated with more regular cusp spacings.

#### *Data set B*

The unrotated factor matrix for data set B is presented in Table 3.9.

Table 3.8 Principle components unrotated solution for factors accounting for &gt;5% variance (Data set A).

Only loadings exceeding 0.5 are listed (See Table 3.4 for variable definitions).

Variable	Factor I	Factor II	Factor III	Factor IV	Factor V
H <sub>b</sub>		-0.694			-0.651
T <sub>i</sub>		0.554		0.617	
W S		-0.939			
W T	-0.829				
φ e		-0.805			
φ h	-0.659		-0.601		
So e	-0.786	-0.528			
So h	-0.792				
Sk e	-0.527		-0.701		
Sk h	0.811				
χ <sub>s</sub>	-0.922				
λ	0.941				
λ <sub>e</sub>	0.906				
% λ	-0.565				0.642
β <sub>m</sub>	0.945				
β <sub>h</sub>			-0.789		
β <sub>e</sub>	0.580				
Exp	.906				
Se	0.794				
% Total variance	48.6	15.8	12.2	7.8	6.0

Table 3.9 Principle components unrotated solution for factors accounting for &gt;5% variance (Data set B).

Only loadings exceeding 0.5 are listed (See Table 3.5 for variable definitions).

Variables	Factor I	Factor II	Factor III	Factor IV	Factor V
H <sub>b</sub>	-0.875				
T <sub>i</sub>		-0.586	-0.647		
TH		0.570	-0.648		
W S				0.808	
W D	0.780				0.501
λ <sub>d</sub>	-0.526	0.751			
% Total variance	31.9	23.4	17.9	15.1	7.8

Factor I (accounting for 31.9 % of the variance in data set B) groups the breaking wave height and the wind direction (WD) and suggests that wind direction influences wave height. The factor also indicates that cusp development ( $\lambda_d$ ) improves with an increase in wave height.

Factor II (accounting for 23.4 % of the variation) groups wave period, the tidal height (TH) and cusp development together. Both the tidal height and cusp development have a positive loading suggesting that cusp development will be enhanced when the tide is in spring dimensions.

There is an association between wave period and cusp development suggesting that longer wave periods result in less well developed cusps.

Factor III groups the tidal height and wave period together. Factor IV groups wind strength (WS) by itself indicating that it is unrelated to any other variables. Factor V (accounting for 7.8 % of the variance) groups wind direction (WD) by itself .

### 3.8 Discussion

For data set A, the principle components analysis indicates that the mean beach slope, the surf zone width, wave type and cusp morphology are associated and account for 48.6 % of the variance within the data set. The relationship between cusp morphology and beach slope is evident in the temporal and spatial distribution of the cusps investigated and beach slope appears to be one of the more influential parameters in the development of a cusped beach. On the eastern Coromandel, cusps form more regularly and consistently on those beaches that have a higher mean subaerial beach face slope (Wharekaho, Hahei and Rings) and less frequently on the lower sloped beaches (Cooks and Buffalo Beaches). Antia (1987) suggests that there may be some critical minimum beach slope and notes that cusps were present on the steeper sections of Nigerian beaches.

Antia (1987) found that mean cusp spacing showed a tendency to increase with increased reflectivity (a function of beach steepness) of beach state. Cusp spacing was smallest on the dissipating (lower sloped) sections of the beach in Antia's study. From the Pearson Product-Moment correlation matrix, there is a significant relationship between cusp spacing and the

subaerial beach slope ( $r=0.880$ ) suggesting that cusp spacing increases as the mean beach face gradient increases. The high loadings on beach slope and cusp spacing in the factor matrix for data set A (Table 3.8) further supports this. Antia (1987) found that the regularity of cusp spacing was better on the steeper beaches, a feature also found in this study where the percentage variation from the mean spacing and the mean beach gradient have a correlation coefficient of  $r=-0.433$ .

Antia (1987) concludes that only one set of cusps tends to occur on low slope beaches whilst multiple sets can occur on the steeper beaches. This correlates reasonably well with data from the eastern Coromandel where the steeper beaches (Maramaratotara ( $5.5-6.0^\circ$ ) and Hahei ( $5.5^\circ$ ) were observed to have two levels of cusps. However, Wharekaho ( $7.3^\circ$ ) and Rings ( $5.5^\circ$ ) beaches, although steep were observed to only have one level of cusps during the observations of this study.

Also of interest is that the more widely spaced cusps on the steeper beaches have a higher elevation and are subsequently better developed and perhaps more stable than those on lower gradient beaches. Cusp spacing, elevation and the mean subaerial beach slope (Table 3.8) have high negative loadings suggesting that on lower sloped beaches, cusps have a smaller spacing and a smaller elevation. The correlation matrix (Table 3.9) shows a correlation coefficient of  $r=0.910$  between cusp spacing and cusp elevation.

The correlation matrix for data set A (Table 3.6) indicates an expected relationship between the mean sediment size of the cusp horn and embayment and the slope of the cusp horn ( $r=0.334$ ) and the slope of the cusp embayment ( $r=0.470$ ). As the mean sediment size increases, the gradient of the cusp horn and embayment increases. The mean effective beach face slope appears more closely associated with cusp spacing than the slopes of the horn and the embayment. The correlations show that the embayment sediment size is unrelated to cusp spacing while as the mean sediment size of the horns increases, the cusps are spaced closer together.

Despite the lack of correlation between grain size and cusp spacing, cusp horns are invariably of coarser sediment than the cusp embayments as found by other investigators (Russel and McIntire, 1965 and Antia, 1987). Dean and Mauremeyer (1981), however, found no difference in

the characteristics of the sediment between the bays and horns of the cusps at Point Reyes and Drakes Beach, California.

The correlation matrix for data set A (Table 3.6) indicates a relationship between cusp spacing and the sorting of the sediment of the horn ( $r=-0.684$ ) and the embayment ( $r=-0.679$ ) sediments suggesting that as cusp spacing increases, the sediment becomes better sorted. As sorting increases, the cusps have a higher elevation and beach slope increases. The improved sorting indicates that more selective sediment transport and increased action by waves has taken place which appears logical as the more widely spaced cusps form on higher energy beaches.

Sorting is better on the horns than the embayments which correlates well with Antia's (1987) observations. This has implications for the slope of the cusp horn and embayment and also for the development of the cusp morphology and swash circulation. Section 3.6 described observations of sediment movement by the action of the swash. Beach gradient depends on the rate of percolation into the sediment. Coarser beaches are steeper because swash percolates rapidly into the sediment faster than it would into finer sediment so there is less backwash to remove sediment resulting in accretion and a steeper beach gradient (Longuet-Higgins and Parkin, 1962; McLean and Kirk, 1969). The rate of percolation is also influenced by the degree of sediment sorting. Because the cusp horns have a larger mean grain size and are better sorted, water percolates quickly. However, the cusp embayments have a smaller mean grain size and are more poorly sorted so less water percolates into the sediment so the velocity and volume of the backwash is such that sediment is eroded. This is the basis for the characteristic swash circulation forming and maintaining the cusp morphology that was observed at all of the investigated beaches. Bagnold (1948) states that the formation of cusps depends on a wide range of sediment sizes being available on a beach so that sorting into the coarse and fine fractions can result in the cusp morphology.

In terms of the skewness of the sediment, the skewness of the horn sediment becomes more finely skewed as cusp spacing increases while the skewness of the embayment becomes coarser as cusp spacing increases.

Also grouped in Factor I of the principle components analysis (data set A) is wave type which is a function of beach slope. Correlation between the two suggests that when the beach is

steeper, the waves are more surging in nature and cusps become spaced further apart. They are also better developed and more regular in their spacing. With surging breakers, the swash extends further up the beach face than plunging breakers suggesting a relationship between swash excursion and cusp characteristics. The correlation matrix for data set A (Table 3.6) shows a correlation coefficient of  $r=0.683$  indicating that cusp spacing increases with increasing swash excursion distance. Longuet-Higgins and Parkin (1962) and Williams (1973) concluded that the dimensions of cusps are related more to the length of the swash than to wave height or period, stating that the mean cusp spacing on a beach is an increasing function of the swash length. Swash excursion increased as the wave type became more surging in nature and the surf zone decreased in width. Swash excursion shows considerable correlation with cusp elevation ( $r=0.729$ ) and the mean beach face gradient ( $r=0.749$ ) implying that swash excursion increases as beach slope increases. This is contradictory to that found by Dean and Mauremeyer (1981) who stated that swash increased with decreasing beach slope.

Cusp morphology is also related to the degree of beach exposure in Factor 1 (data set A) suggesting that cusp spacing increases with increased exposure (essentially an increase in wave energy). It is noted that on the more sheltered beaches (Buffalo and Cooks), the berm is low and the cusps are more closely spaced. Those more exposed beaches (Hahei, Wharekaho, and Rings) face the open sea and are characterised by higher berms and have larger cusp spacing. This is consistent with the findings of Russel and McIntire (1965) who conclude that smaller cusps are associated with poorer exposure and suggest that wave properties associated with 'exposure' should be measured. In contrast to this correlation, Factor II (in data set A) groups wave height, wave period and wave steepness and indicates a pattern in the data in which these are independent of the morphological characteristics.

A relationship between morphology and wave parameters is evident, however, for data set B. Factor I groups wave height and cusp development suggesting that as wave height increases, cusp development becomes better. This does not account for the spacing of the cusps. This is in direct contrast to wave data in data set A but correlates well with the relationship between 'exposure' (as being a measure of wave energy) and cusp development. The lack of correlation with both wave height and wave period with cusp morphology in data set A may be explained by the fact that wave heights and wave periods were measured after cusp formation and may not be related to the conditions that formed the cusps. Wave height, in Data set B, is also related to wind direction where onshore winds correspond to higher

onshore swell, a correlation also observed in the time series data from Rings Beach and observations of the cusp development at Buffalo Beach.

Williams (1973) found no statistically significant correlation between wave height and cusp spacing or development. However, Longuet-Higgins and Parkin (1962) found a proportional increase in cusp spacing with increasing wave height but a better correlation with swash excursion. Sallenger (1979) observed progressive longshore change along a beach from a ridge and runnel system through to well developed cusps and suggested that this was due to changes in wave energy along the beach due to refraction, where wave energy was at a maximum where the cusps developed and at a minimum where there were no cusps. Sallenger concluded a relationship between energy and cusp development. This is evident in the time series data from Rings Beach (section 3.4.2) where the location of the cusps on the beach was influenced by wind and swell direction and sheltering from headlands at either end of Rings Beach.

Factor II on data set B (Table 3.8) groups wave period and the tidal range with cusp development, indicating that the wave period becomes longer as the tidal height increases. Cusp development is more likely under these conditions. Tides are thought not to be important in the development of cusps (Komar, 1976) but the Coromandel data suggests that as the tide approaches spring proportions, the likelihood and the degree of cusp development increases. This is probably because water levels are higher, reaching the steeper part of the beach face. As previously indicated, cusps are more likely to form on a steeper, more reflective beaches.

Wind strength appears to have little influence on cusp development accounting for 15.1 % of the variance in data set B.

Principle components analysis and the Pearson Product-Moment correlation coefficient semi-quantifies morphological data but more qualitative observations can be suggested regarding cusp morphology.

Results from this study indicate that those cusps on the upper foreshore have a greater stability compared to the lower set which are more changeable. The higher set of cusps can only be affected by spring tides or higher energy whereas the lower level can be affected by normal tide and wave energy fluctuations. The higher level of cusps invariably have a larger spacing than the set more seaward which is agreement with the literature (Williams, 1973;

Antia, 1987). Williams (1973) and Komar (1976) suggest that higher cusps are formed by larger waves. This further supports an association between wave energy and cusp development indicated in the statistical analysis of data set B.

Cusp formation and development was a result of selective erosion and accretion of the beach face. The cusps at Buffalo and Kuaotunu Beaches were a result of net accretion of the foreshore, indicated by no significant change in the slope of the beach face above or below the embayment suggesting that the horns are accretionary. Antia (1989) found that during 44 instances of beach cusp occurrence, 55% of the cases were a result of erosion and 45% were a result of accretion of the beach face. The cusps at the other beaches investigated developed in the berm and there is no information to determine whether they are accretional or erosional. The lower wave steepness values and the low wave energy at most of the beaches indicate an overall accretion of the beach face.

From the time series data, it can be suggested that cusps develop during the transition from high energy to low energy when long period swell waves approach parallel to the beach. This is in agreement with other investigations (Russel and McIntire, 1965; Antia, 1987). High energy and short period wind waves tend to destroy the cusps. Seymour and Aubrey (1985) also noted that high frequency energy with little swell wave contribution destroyed cusps. There appears to be a range of energy between which cusps can form. If wave heights are too large for the dimensions of the cusps, they will be destroyed, especially if accompanied by short period waves. There also appears to be some minimum wave energy level below which cusps will not form. As beach slope is a function of wave energy, low wave heights result in lower beach slopes, wider, more dissipative surf zones inhibiting cusp development or forming closely spaced, poorly developed cusps.

The cusps on the eastern Coromandel do not change in spacing and morphology in response to small changes in wave conditions but remain stable until some significant changes in conditions .

### **3.9 Conclusion**

In summary, it can be suggested that morphological development of a cusped beach is controlled by the interaction of numerous parameters. The most influential parameters appear

to be the mean beach slope and wave energy. These parameters do not explain the initiation of cusp formation, but changes in these parameters do account for changes in cusp morphology. It appears that cusps are more likely to form when several variables are favourable.

The degree of cusp development increases with increasing wave energy to some maximum wave energy level after which the cusps are destroyed. There also appears to be a minimum wave energy level (and a minimum beach slope) below which cusps will not form. Therefore changes in energy along the beach result in some areas of the beach being more suitable for cusp development.

The cusped morphology is controlled by the action of the swash (a function of wave energy, beach slope, surf zone width and breaker type) and it is swash circulation that sorts the sediment into the coarse and fine fractions that make up the cusp horn and embayment respectively.

The mean sediment size of the beach face determines the mean beach slope and in turn affects the type of waves present on the beach, the degree to which the beach can reflect or dissipate wave energy. These parameters influence the development of the cusps.

Although the evidence is far from conclusive, data gathered from the eastern Coromandel is in general agreement with investigations done previously in other parts of the world. The observations of this chapter do not explain the initiation of cusps or explain the regularity of the cusp spacing. It appears there is some other mechanism or combination of processes that initiate cusp development. Current theory suggests that edge waves can account for this and the theory and practical application of the theory on the eastern Coromandel is investigated in the following chapter.



## *Chapter Four*

### *Theoretical implications of edge waves for the development of a cusped beach*

#### **4.1 Introduction**

The initiation and control on the spacing of beach cusps is not fully understood and previous studies have resulted in a great deal of contradictory literature. Edge waves are thought to best account for the initiation and spacing of beach cusps. The theory of edge waves can be utilised to predict the spacing of beach cusps on a beach of a given slope and wave period.

This chapter investigates the theory of edge waves and examines the methods by which beach cusp spacing can be predicted from edge wave dynamics. The theory of edge waves is applied to the beaches studied to investigate how applicable it is and to assess whether it predicts the spacing of cusps on the eastern Coromandel and to what degree of accuracy.

#### **4.2 Edge wave theory**

##### **4.2.1 Infragravity waves**

Infragravity waves are defined as those waves that have a period between 20 - 200 seconds that are associated with the surf zone. The period of infragravity waves is a function of the formative mechanism (which may be a result of external wave groupiness or generated internally by wave transformations), and the gradient of the surf zone over which they operate. Infragravity energy is not limited by wave breaking but rather becomes more

influential close to the shoreline as offshore wave energy increases (Holman and Sallenger, 1985).

Infragravity energy is propagated as standing waves in the surfzone where the incoming incident wave and infragravity waves interact with totally or partially reflected waves of a similar period. If the reflected wave radiates energy out to sea, long-crested 'leaky-mode' standing waves result (Howd *et. al.*, 1990). No significant shore-parallel variations result from this (Suhayda, 1974).

If infragravity waves are trapped nearshore by refraction, edge waves can occur. Edge waves cannot radiate energy seaward; energy can only be dissipated through friction and through interaction with currents and other waves. Edge waves may be progressive or standing in the alongshore direction, their amplitude varying approximately sinusoidally along the shore and diminishes rapidly seaward of the shoreline (Schaffer and Jonsson, 1992). Essentially, the effect of an edge wave is a periodic longshore variation in the set-up.

The generation of edge waves involves two processes. Firstly, an initial perturbation, and then the excitation of that disturbance with sufficient strength to lead to edge wave growth and maintenance. The initial perturbations are inherent to most systems and are due to pressure fluctuations associated with wind stress, and the refraction and reflection of incident waves from headlands and other structures (Bauer and Greenwood, 1991). Fig. 4.1. illustrates the motion of an edge wave alongshore.

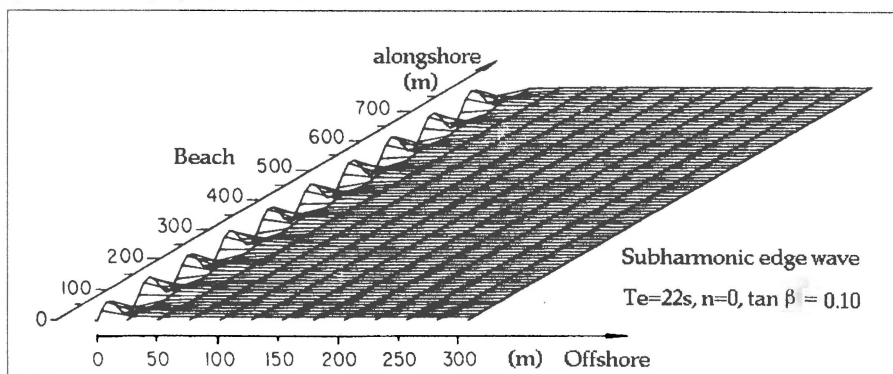


Figure 4.1. Instantaneous water surface topography associated with a subharmonic edge wave (Wright and Short, 1984).

#### 4.2.2 Edge wave modes

Edge wave theory is well established. The wavelength of an edge wave (m) is given by Ursell (1952) as:

$$L_e = g/2\pi T_e^2 \sin [(2n + 1) \beta], \quad 4.1$$

where  $T_e$  is the edge wave period (s),  $g$  is the gravitational acceleration ( $9.81\text{m/s}^2$ ),  $n$  is the modal number and  $\beta$  is the beach slope ( $^\circ$ ).

Ursell (1952) showed that a family of edge wave modes can occur on a beach of constant slope. The edge wave modes ( $n$ ) denote the offshore behaviour of the wave. The lowest order mode ( $n=0$ ), decays exponentially offshore, while for other modes, the modal number gives the number of zero crossings of the amplitude in the offshore direction before eventual offshore decay (Huntley and Bowen, 1975). Fig. 4.2 shows the offshore structure and behaviour of edge waves. The profile of a wave normally incident from deep water and totally reflected from the beach face is also shown.

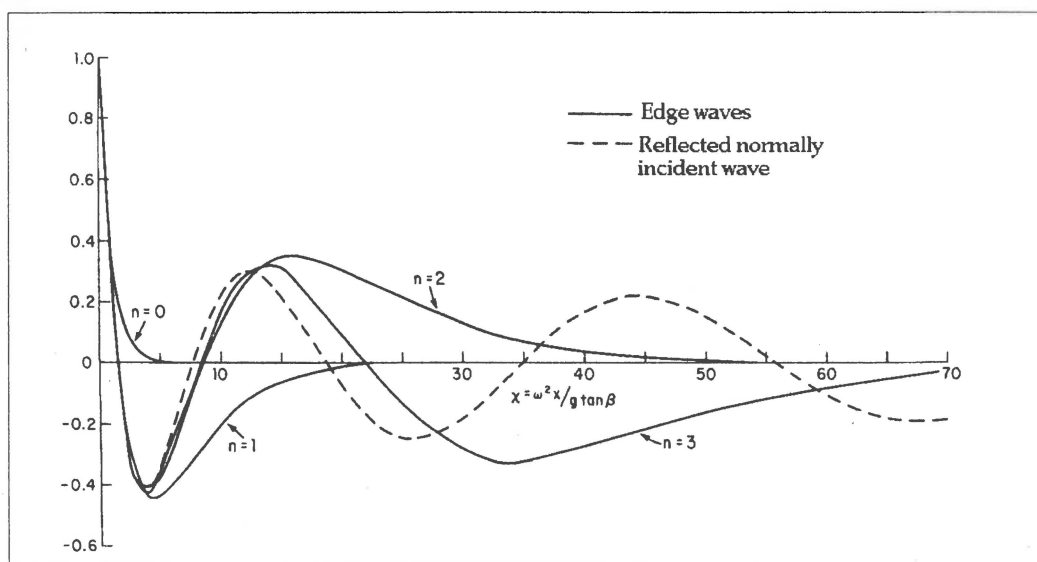


Fig. 4.2 Offshore dependence of profiles of edge waves of modes  $n=0,1,2,3$  and of normally reflected incident waves, in terms of the dimensionless variable  $\chi = \omega_e^2 x / g \tan \beta$  (Guza and Inman, 1975).

The mode of an edge wave ( $n = 0,1,2,\dots$ ) is limited by the cutoff:

$$(2n + 1)\beta < \pi/2, \quad 4.2$$

(Ursell,1952). So, for a given edge wave period, there are a series of possible wavelengths corresponding to the possible values of  $n$ . Those waves with periods larger than the cut-off are not trapped and radiate energy away from the nearshore zone. The number of edge wave modes that can exist on a beach is essentially a function of beach slope, increasing with decreasing beach slope.

Bowen and Inman (1978) state that there may be a cut-off frequency for which edge waves can be predicted. For a profile of linear slope ( $\beta$ ) to a distance offshore,  $\chi_s$  (roughly the width of the surf zone), Bowen and Inman (1969) express the non-dimensional nearshore width as:

$$\chi_s = \omega_e^2 \chi_s / g \tan \beta, \quad 4.3$$

where  $\omega_e$  is the radian frequency of the edge wave. Seawards of  $\chi_s$  the depth is constant ( $\beta=0$ ).  $\chi_s$  must exceed a minimum value:

$$\chi_s > \chi_{\min}, \quad 4.4$$

where  $\chi_{\min}$  is the minimum beach width, a function of the mode number, below which mode  $n$  cannot be trapped (Bowen and Inman, 1969).

$$\chi_{\min} = 3.5 n(n+1). \quad 4.5$$

As a 'rule of thumb', the value of  $\chi_{\min}$  is  $(2n+1)^2 \cdot \chi_s$  and  $\chi_{\min}$  provides for a series of periods up to a maximum period, expressed as:

$$T_{ep} = 2\pi (\chi_s / g \tan \beta \chi_{\min})^{1/2}. \quad 4.6$$

The cut-off mechanism predicts edge wave periods, each corresponding to a given mode number.

The maximum breaking wave height that can lead to subharmonic excitation is given by Guza and Inman (1975) as:

$$H_{\max} = g T_i^2 \tan^2 \beta / \pi^2. \quad 4.7$$

This corresponds to the transition region between surging and plunging breakers as defined by Galvin (1972).

The minimum incident wave height for zero-mode subharmonic excitation is:

$$H_{\min} = 10.2 (\nu T_i / \pi)^{1/2}, \quad 4.8$$

(Guza and Inman, 1975), where  $\nu$  is the kinematic viscosity.

#### 4.2.3 Synchronous and subharmonic edge waves.

The simplest edge wave model is that of a synchronous edge wave with a period ( $T_e$ ) equal to the period ( $T_i$ ) of the forcing incident waves (Bowen and Inman, 1976). Guza and Inman (1975) experimented on reflective plane laboratory beaches and found that initially large subharmonic edge waves ( $T_e = 2T_i$ ) moved sand tracers into beach cusp shapes. Guza and Inman (1974) found that it was more common for edge waves with periods greater than  $T_i$  to grow by a weak resonant interaction between the incident wave and two edge waves of periods  $T_{e(1)}$  and  $T_{e(2)}$  travelling in opposite directions alongshore.

Guza and Davis (1974) found that for subharmonic edge waves, the zero mode was the likeliest to occur. Huntley and Bowen (1973) measured edge waves on the south eastern coast of England and also found that the edge waves were a zero-mode subharmonic of the incoming waves. Bowen and Inman (1969) produced similar subharmonics in wave basin experiments. Subharmonic edge waves are the most easily excited, requiring the smallest incident wave height. A subharmonic edge wave has a period that is twice that of the incident wave, so the incident wave is alternately in phase with portions of the edge wave that differ by longshore separation of  $L_e/2$ . Fig. 4.3 illustrates a subharmonic edge wave in the nearshore zone.

Therefore, referring to Equation (1) and following from the above, the cusp wavelength associated with a  $n=0$  mode synchronous and subharmonic edge waves are given as:

$$\lambda_c = L_e/2 = g/\pi T_e^2 \tan \beta \quad (\text{subharmonic}) \quad 4.9$$

and

$$\lambda_c = L_e = g/2\pi T_e^2 \tan \beta \quad (\text{synchronous}) \quad 4.10$$

For synchronous edge waves, where  $T_e = T_i$ , the passage of every incident wave crest will cause a longshore spacing of wave height maximums equal to one synchronous edge wave wavelength (Bowen and Inman, 1969).

For subharmonic edge waves, where  $T_e = 2T_i$ , wave height maximums will alternate with wave height minimums on the passage of every incident wave crest since the edge wave completes only one half cycle between successive incident waves.

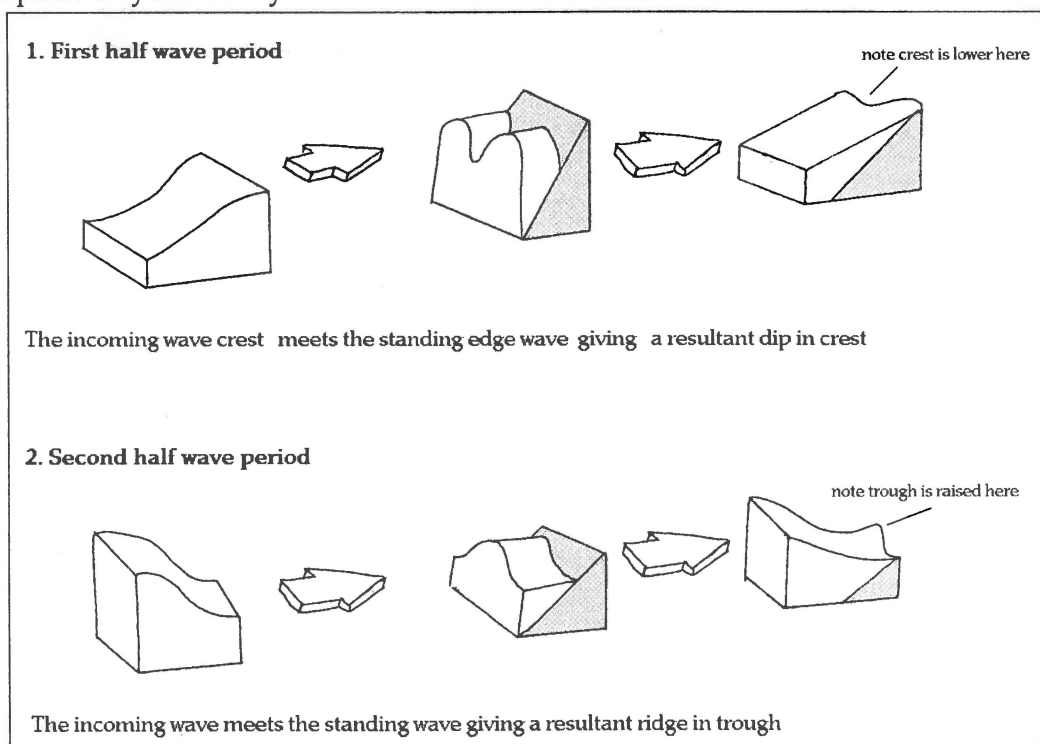


Figure 4.3 Interaction of an edge wave and incident waves in the nearshore zone (Pethick, 1984). The incident wave crest passes over the edge wave causing an undulation in the incident wave crest. Half a period later, the incident wave crest passes over the edge wave to form an increase in the incident wave height at the same position relative to the shoreline as the previous decrease in height. This results in a series of undulations in wave height at regular intervals along the shoreline. With synchronous edge waves and incident waves, every incident wave runup is the same and the longshore spacing of runup are equal to the edge wave wavelength.

A review of the literature shows that zero mode edge waves are the most likely to occur and a zero mode edge wave is the most common used when predicting the spacing of beach cusps. A

Table 4.1 Summary of previous investigations carried out to assess the applicability of edge waves as a causative mechanism of beach cusps.

Researcher	Location	Cusp spacing (m)	$T_i$ (s)	$H_b$ (m)	$\beta$ (°)	Wave type	Edge wave type	Comments
Lonquet-Higgins and Parkin (1962)	Field data Chesil Bank, England	3.7-10.0	5.0-7.0	-	5.1-11.3	-	sub-harmonic n=0	disputed edge wave mechanism finding no relationship between wave period or the wave length of theoretical edge waves.
Komar (1973)	field data from Mono Lake.	0.11-0.60	1.0-2.0	-	3.0-7.0	surging	subharmonic n=0	found a good correlation between observed and predicted
Guza and Inman (1975)	laboratory	-	-	-	-	-	synchronous and subharmonic	laboratory experiments involved different parameters, created edge waves that moved sediment into cusps.
Dubois (1978)	field data	26.5-39.6	8.5	0.09	5.7-8.3	plunging	subharmonic n=0	found a good correlation but couldn't conclude a relationship because of the variability of the cusp spacing.
Huntley and Bowen (1978)	field data	12.0	6.9	-	4.6	-	subharmonic n=0	found a close agreement between the predicted and measured cusp spacing.
Sallenger (1979)	field data	10.0	6.5	-	4.0	plunging breakers	subharmonic n=0	found a good correlation.
Dean and Mauremeyer (1980)	field data	23.3	15.4	-	2.2	-	subharmonic n=0	found little agreement and state that $T_i$ is too variable for the theory to be applicable.

Table 4.1 continued

Guza and Bowen (1981)	laboratory data	1.3	2.7s	-	6.0	-	subharmonic	concluded that subharmonic edge waves formed the cusps
Kaneko (1985)	laboratory data	-	0.5-2.5	2.7-4.2	4.63-8.0	-	subharmonic n=0	found close agreement between predicted and measured spacing.
Seymour and Aubrey (1985)	field data	16.0-48.0	5.0-18.0	1.5	20.0	plunging- surging breakers	subharmonic n=0	found close agreement between predicted and measured spacing
Miller et. al. (1989)	field data	22.0-47.0	10.0-12.0	-	4.0-6.0		subharmonic n=0	found close agreement with predicted and measured spacing

summary of previous studies that have used the theory of edge waves to predict cusp spacing are presented in Table 4.1.

#### 4.2.4 Edge waves and beach cusp initiation, formation and maintenance

Bowen and Inman (1971) noted that the drift velocity patterns above the bottom boundary layer due to subharmonic edge waves were similar to commonly observed rhythmic nearshore features. They stated that sediment suspension takes place in response to incident wave stresses, but edge waves provide the ordered perturbation that causes sediment to drift to zones of convergence where it accumulates.

It is thought that beach cusps are a result of the finite amplitude of an edge wave at the shoreline, which results in a sinusoidal variation in the run-up amplitude along the shore. Application of edge waves to beach cusp development involves the influence on swash of regular longshore variation in wave height as a result of edge wave-incident wave superposition. There is no motion at the edge wave nodes but excursion up and down the beach at the antinodes. Erosion can be expected at the antinodes and the cusp horns correspond to the edge wave nodes which forms a set of cusped features with a wavelength of  $L_e/2$  where  $L_e$  is the wavelength of the edge wave (assuming a subharmonic edge wave) (Fig 4.4).

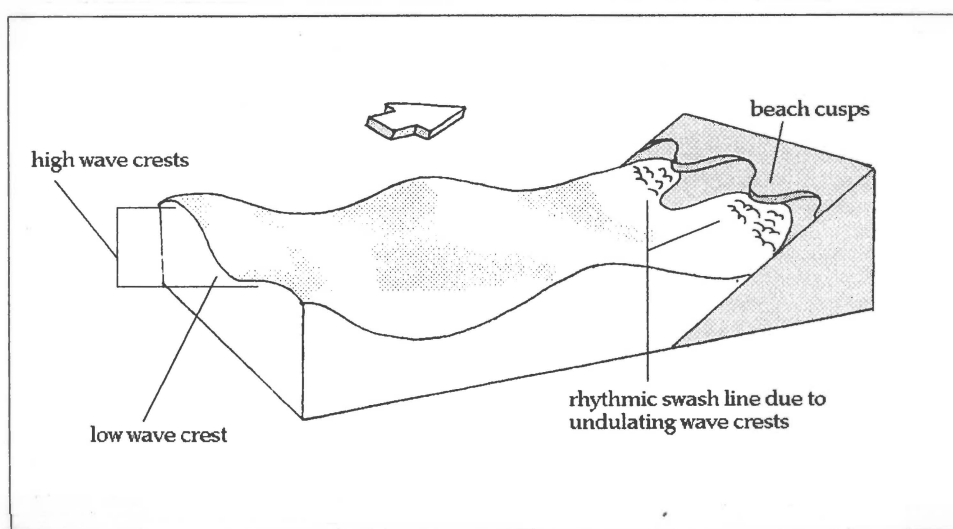


Fig 4.4 Interaction of sinusoidal variation in wave height due to a subharmonic edge wave and the formation of cusps (adapted from Pethick, 1984). The rhythmic spacing of the high and low wave crests caused by edge waves is thought to be responsible for the regularity of the cusp spacing.

### 4.3 Discussion

The incident wave period ( $T_i$ ), the mean subaerial beach slope ( $\beta_m$ ) and mean cusp spacing for each observation period (from Chapter 3) are used in the predictive model.

To investigate different edge waves, the actual measured cusp spacing from the eastern Coromandel data is plotted against the errors (%) involved in the prediction of cusp spacing using a subharmonic edge wave ( $T_e = 2T_i$ ) where  $n=0$ , and two synchronous ( $T_e=T_i$ ) edge waves ( $n=0$  and  $n=1$ ) (using Eq. 4.9 and 4.10) (Fig 4.5).

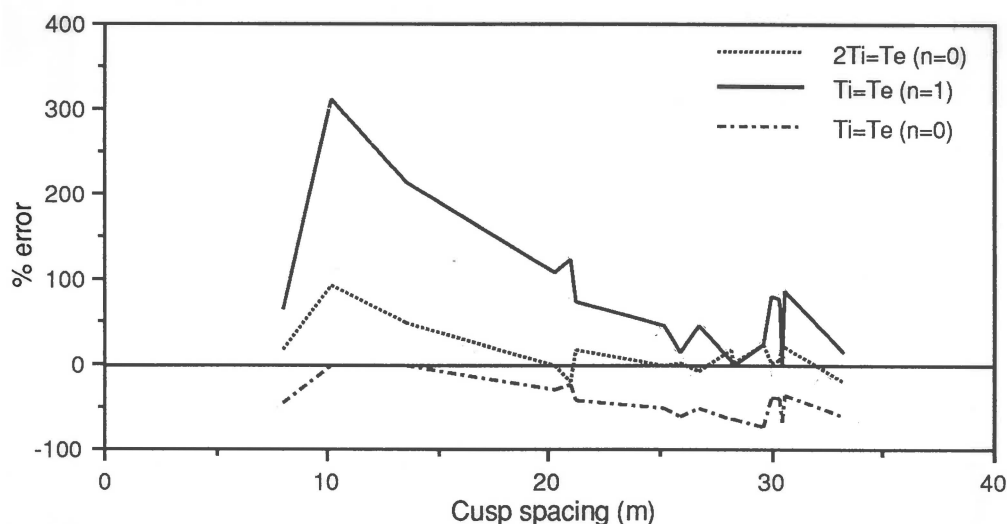


Figure 4.5 Measured cusp spacings compared with the % error of the predicted cusp spacings using edge wave theory utilising a subharmonic edge wave ( $T_e=2T_i$ ) and synchronous edge waves ( $T_e=T_i$ ) where  $T_e$  is the edge wave period (s) and  $T_i$  is the incident wave period (s).

The subharmonic edge wave ( $n=0$ ) gives the most accurate predictions for most cusp spacing except for those cusps between 10.0-15.0m. The synchronous wave generally underestimates cusp spacing except for those more closely spaced cusps where a mode zero, synchronous wave is the more accurate predictor of cusp spacing. The synchronous ( $n=1$ ) edge wave severely overestimates cusp spacing especially for the more closely spaced cusps. The smaller cusp spacings are on the less steep beaches. On these beaches, less wave reflection may result in synchronous rather than subharmonic waves being excited.

As the modal number describes the offshore behaviour of the edge wave, higher numbers of modes can exist when the beach slope is lower and the system is more dissipative. Bars are thought to be a result of the zero crossings of edge waves in the offshore direction (Aagard,

1990). The more zero crossings (and the higher the mode), the more bars (e.g.  $n=2$  results in the formation of two bars). As no bars were present on the cusped beaches and the systems were reflective, a zero mode subharmonic edge wave may be the more likely to exist.

A subharmonic edge wave of  $n=0$  is assumed for the rest of the analysis.

Table 4.2 Predicted edge wave dynamics and cusp spacing where  $H_{\max}$  is the maximum breaking wave height that can lead to subharmonic excitation,  $H_{\min}$  is the minimum breaking wave height that can lead to subharmonic excitation,  $\chi_s$  is the width of the surf zone,  $T_{ep}$  is the predicted period of the edge wave,  $T_e=2T_i$ ,  $\lambda_c$  is the predicted cusp spacing using a subharmonic, zero mode edge wave and  $\lambda$  is the measured cusp spacing.

Date	Beach	$H_{\max}$ (m)	$H_{\min}$ (m)	$\chi_s$	$T_{ep}$ (s)	$T_e$ (s)	$\lambda_c$ (m)	$\lambda$ (m)
7/92	Buffalo	0.12	0.019	10.00	30.59	16.7	9.49	8.08
4/91	Buffalo	0.33	0.022	9.00	26.39	22.0	19.77	10.26
3/91	Buffalo	0.40	0.020	9.00	23.79	19.6	19.35	20.30
5/92	Cooks	0.27	0.019	7.80	24.57	17.2	16.34	21.07
8/92	Hahei	0.83	0.018	2.50	10.03	18.0	24.26	26.74
5/92	Hahei	0.92	0.019	3.50	12.11	18.0	29.95	30.02
3/91	Kuaotunu	0.33	0.022	2.00	24.88	23.2	19.77	13.52
7/92	Maramaratotara	0.69	0.019	2.00	8.76	15.8	25.83	25.91
8/92	Maramaratotara	0.77	0.018	3.00	11.10	18.0	24.70	21.27
5/92	Maramaratotara	0.82	0.019	3.00	15.24	18.1	28.32	28.33
3/92	Maramaratotara	1.10	0.022	3.00	10.16	20.0	32.67	28.20
8/92	Rings	0.75	0.018	9.00	19.42	18.0	24.26	25.17
5/92	Rings	0.99	0.020	10.00	20.16	19.6	31.04	30.43
3/91	Rings	1.12	0.021	6.00	15.86	22.0	36.24	30.61
3/92	Rings	1.12	0.022	7.00	17.13	22.0	36.24	29.69
7/92	Wharekaho	1.10	0.018	1.50	6.74	15.8	25.83	33.31
5/92	Wharekaho	1.5	0.020	2.00	8.12	17.7	38.12	30.55

In terms of the cut-off (Eq. 4.2), the beaches investigated are all within the slope range where subharmonic edge waves can theoretically exist. The lower sloped beaches - Buffalo, Kuaotunu and Cooks, can have higher modes than the steeper beaches - Wharekaho, Rings, Hahei and Maramaratotara. There is a theoretical minimum beach slope below which

insufficient wave energy is reflected to produce stand waves which in turn can drive edge waves (Fig. 4.6).

Utilising Eq. 4.8 and 4.9, the maximum and minimum breaking wave heights that can lead to subharmonic excitation on the beaches investigated is tabulated in Table 4.2. The calculated  $H_{\max}$  is dependant on the wave period and beach slope. This shows that subharmonic edge waves can occur on the steeper beaches over a greater range of wave heights than the less steep beaches. The theory states that above a certain wave height, edge waves will not form. This may be due to the fact that waves greater than the maximum wave height are associated with short-swell storm conditions where the beach is dissipative and not reflecting energy from the shoreline. Long period, even waves on reflective beaches are thought to be needed for cusp formation.

The minimum wave height ( $H_{\min}$ ) (Table 4.2) leading to subharmonic excitation is dependant on wave period and does not vary greatly between beaches, being approximately 1.0-2.0 cm suggesting that the minimum wave height for edge wave excitation is insignificant. As discussed in Chapter Three (and investigated further in Chapter Seven), the spatial distribution of cusps on a beach appears to be controlled by changes in wave energy along the beach, cusps form where the energy is higher. It appeared there was a minimum wave height below which cusp development would not take place. Being a function of wave period, the minimum wave height does not vary greatly between beaches and is approximately 1.0-2.0 cm suggesting that the minimum wave height for subharmonic excitation is insignificant. Theory states that below the minimum wave height, incident and edge wave interaction does not lead to edge wave growth because of the greater viscous damping of the edge wave.

The theoretical edge wave period that can exist, ( $T_{ep}$ ) is a function of edge wave mode, surf zone width and beach slope, differs somewhat from that estimated visually from the beach ( $T_e$ ) (Table 4.2). The results are somewhat inconsistent because as slope increases, the width of the surf zone decreases. As the  $T_{ep}$  is in part a function of the surf zone width, this implies that as slope increases, the maximum edge wave period possible on a beach of that slope decreases. And, as a result, the predicted cusp spacing due to a subharmonic mode 0 edge wave (Eq. 9) decreases as the beach slope increases. This is in contrast to what has been observed in the field, and discussed in Chapter 2, where cusp spacing increased with increasing beach slope.

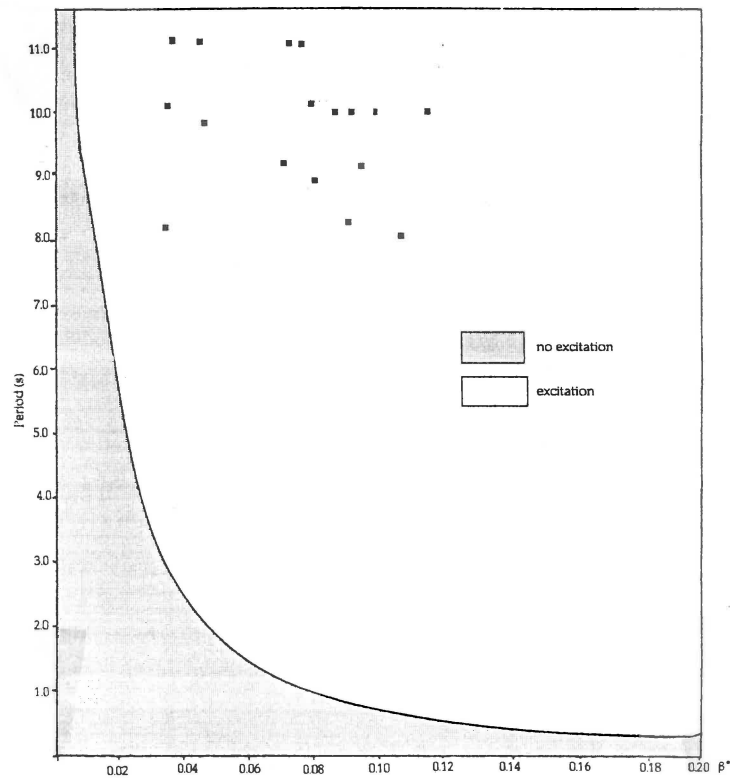


Figure 4.6 Minimum incident wave periods for  $n=0$  subharmonic excitation as a function of beach slope (adapted from Guza and Inman, 1975). Data from this investigation are plotted as ■ and indicates that subharmonic edge waves could theoretically occur on the beaches studied.

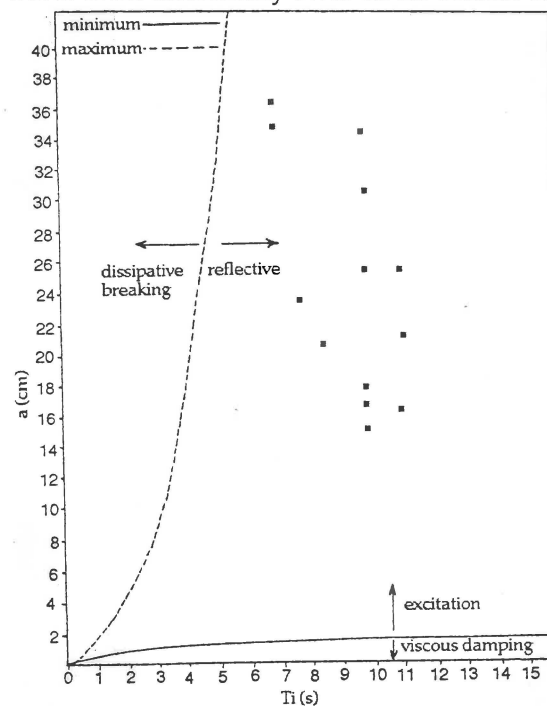


Figure 4.7 Theoretical boundaries for excitation of zero mode subharmonic edge waves as a function of incident wave period and amplitude (Adapted from Guza and Inman, 1975) data from this study are plotted as ■ and adds further support to the theory that edge waves could exist on the beaches investigated.

All Coromandel data falls within the range of incident wave periods and beach slopes where subharmonic excitation would be expected according to the experiments of Guza and Inman (1975) (Fig 4.7) indicating that theoretically edge waves could be present on these beaches.

The data also plots within the area where a subharmonic edge wave can be excited as a function of incident wave period and amplitude (Fig 4.7).

The spatial distribution of cusps on a beach can also be theoretically explained using edge wave theory. A curving shoreline (for example Wharekaho and Buffalo Beaches) can provide end effects which limit the spatial extent over which resonance occurs leading to localised edge wave excitation. In turn, if cusps are due to edge waves, this may lead localised cusp formation (Inman and Guza, 1975).

It has been shown from the theory, that the morphology and wave climate of the beaches investigated is such so that edge waves could theoretically exist. But this does not indicate that edge waves are responsible for the initiation and formation of cusps on these beaches. Using Eq. 4.9, and utilising the observed wave period ( $2T_i = T_e$ ) and assuming a subharmonic zero mode edge wave, the predicted cusp spacing is calculated and tabulated in Table 4.2. Using values from Table 4.2, measured cusp spacings are plotted against the predicted cusp spacing (Fig 4.8).

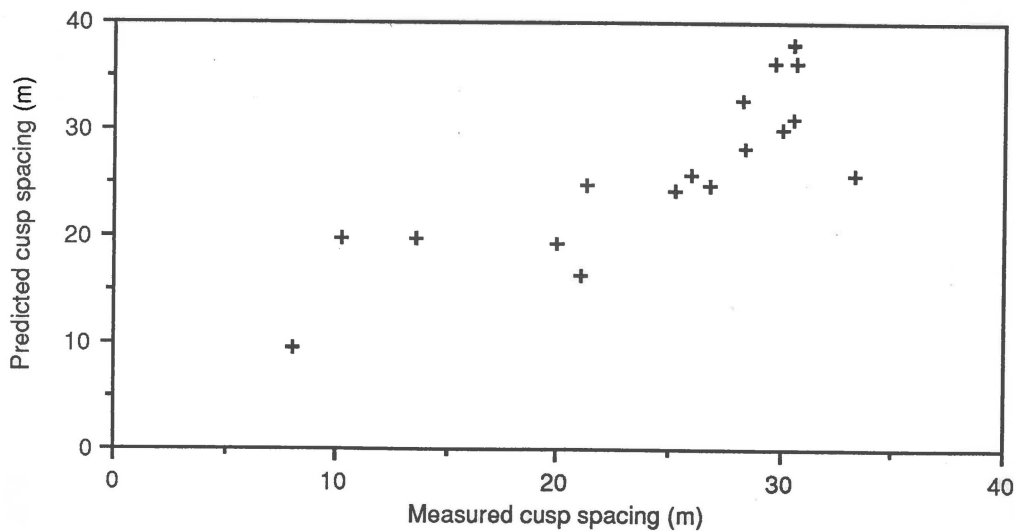


Fig. 4.8 Measured cusp spacing ( $\lambda$ ) versus predicted cusp spacing ( $\lambda_c$ ) based on edge waves using data from Table 4.2 ( $r=0.774$ ).

A correlation co-efficient of  $R= 0.774$  is obtained with some scatter. Inman and Guza (1982) also noted significant scatter in a similar plot using data from the literature and suggested that this is due to the difficulty in assigning a single incident wave period (required in Eq. 4.1) to the spectra of naturally occurring waves. Dean and Mauremeyer (1981) found significant deviation from the mean when they measured the periods of 100 consecutive waves during an episode of cusp formation and concluded that edge waves did not determine the wavelength of the cusps because of the variability in wave period. Inman and Guza (1982) suggest that a mean incident wave period is the most sensible to use in the calculation of the predicted cusp wavelength and to associate any uncertainty in the wavelength prediction with uncertainties in  $T_i$ . Inman and Guza conclude that the correspondence between the predicted and observed cusp wavelengths is strong evidence that subharmonic edge waves frequently control the longshore wavelength of beach cusps.

Figure 4.9 shows predicted cusp spacing plotted against measured cusp spacings using data from previous investigators including data from this study (see Table 4.1). A significant correlation is evident in this previous work and also in the Coromandel data ( $r = 0.940$ ).

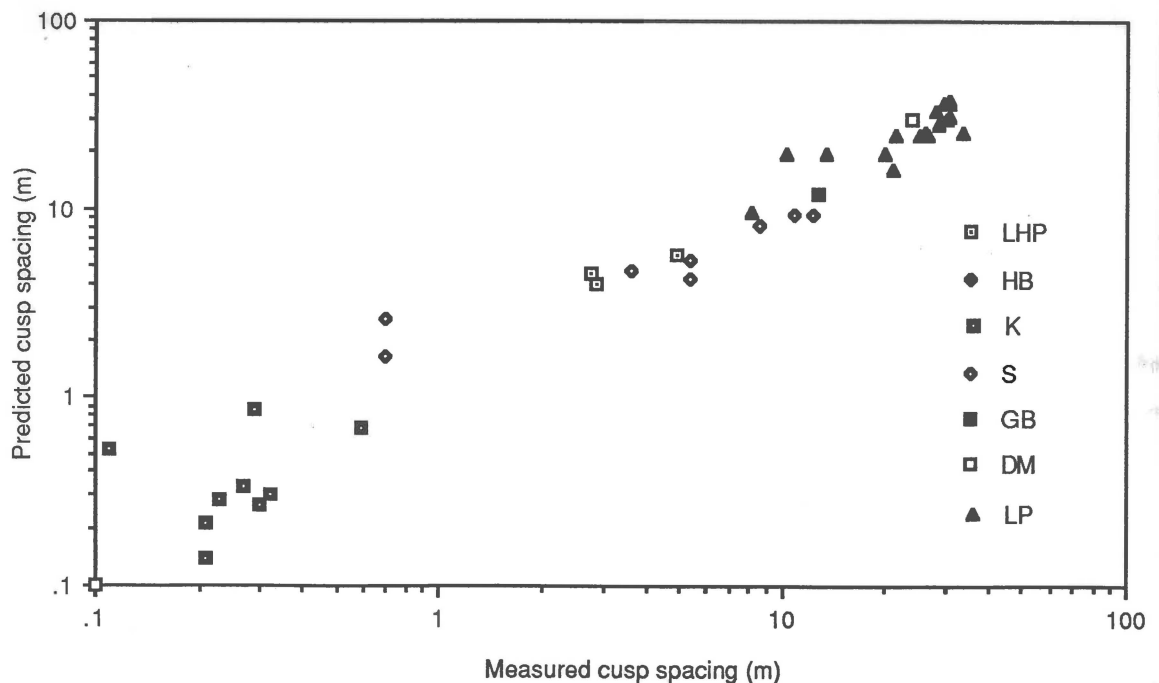


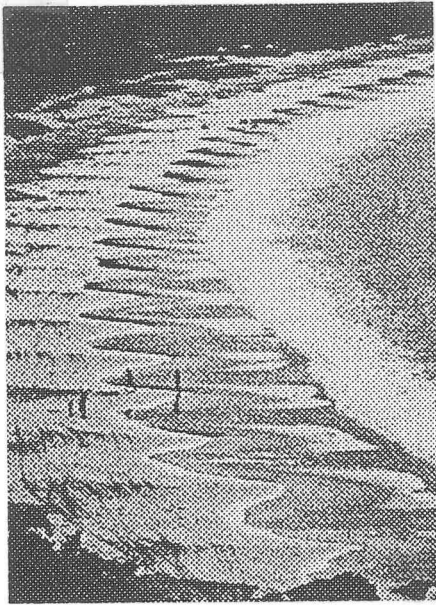
Figure 4.9 Measured cusp spacing ( $\lambda$ ) plotted against predicted cusp spacing ( $\lambda_c$ ) using data from Longuet-Higgins and Parkin (LHP), 1962; Huntley and Bowen (HB), 1978; Komar (K) 1973; Sallenger (S), 1979; Guza and Bowen (GB), 1981; Dean and Mauremeyer (DM), 1981 and data from this study (LP).

## 4.4 Conclusion

Utilising edge wave theory, it can be suggested that edge waves could theoretically occur on the beaches that have been investigated because they all have suitable wave climates and beach slopes. However, there is little evidence to suggest that the cusps present on these beaches were formed by edge waves. Using a subharmonic zero mode edge wave, a significant correlation was found between the predicted and measured cusp spacing but this is not conclusive.

The results of the principle components analysis of the previous chapter illustrated a lack of relationship between wave period and cusp spacing (Data set A). The wave length of an edge wave is a function of incident wave period. The lack of relationship between cusp spacing and the wave period disputes edge waves as a causative mechanism. However, the wave period estimated for each beach may be inaccurate because the period was measured after the formation of the cusps and may not be relevant to those conditions that initiated cusp development and may account for any inconsistencies. Still, wave period does not vary between the beaches at one time because of the close vicinity of all the beaches. Wave period doesn't vary though cusp spacing does and beach slope does. It therefore appears that beach slope is a better indicator of cusp spacing than wave period. This may explain the convincing correlation between the predicted and measured cusp spacings as the edge wave wavelength is a function of both wave period and beach slope. Because it is inversely proportional to  $T_e^2$ , changes in period have lesser effect than changes in beach slope indicating that the prediction of beach cusp spacing is largely controlled by beach slope (*pers. comm.* de Lange, 1992).

The possible existence of edge waves has been investigated theoretically in this chapter. The following chapter expands on this further and uses the Wright-Short model of beach classification to investigate how topography and wave conditions interact to initiate and determine the characteristics of wave resonance.



## *Chapter Five*

### *Morphological beach state and beach cusp occurrence*

#### **5.1 Introduction**

The morphology of a beach is the result of the interaction of processes acting upon the shoreline. Morphology is determined by wave height, which controls runup and the amount of energy impacting the beach; wave period, which controls the rate at which the beach receives this energy; and sediment size, which influences sediment transport and the beach slope. When one of these parameters changes the beach adjusts in response. A beach can develop a modal or most re-occurrent morphology as a result of the prevailing conditions.

Several beach morphology models have been developed to classify beach types and to explain changes in beach state (Davis and Fox, 1972; Dean, 1973; Sunamara, 1985). The Wright and Short model is a morphological classification that classifies beaches into six different beach states by combining wave energy, period and sediment size. Each of these beach states has characteristic dominant beach-surf zone morphology and associated hydrodynamics.

Beach morphology is related to beach cusp existence, cusps being more common on steeper beaches where the incident wave is strongly reflected (Guza and Inman, 1975 and Antia, 1987). This chapter discusses the beach state of those beaches studied in terms of the Wright and Short morphological model and investigates cusp formation in respect to changes in conditions that lead to changes in beach morphology.

## 5.2 Wright and Short model of morphological beach states

Wright and Short (in conjunction with other researchers) investigated south-eastern and eastern Australian beaches to determine the factors that cause morphodynamic changes. Their work resulted in the development of six common morphodynamic beach states defined as dissipative, longshore bar trough, rhythmic bar and beach, transverse bar and rip, ridge and runnel or low tide terrace, and reflective states (Fig. 5.1). The state of a beach depends on the local environmental conditions, sediments and antecedent wave conditions.

### 5.2.1 Beach States

The following outlines the characteristics and associated environmental conditions of each of the six beach states. Short and Wright (1983) discuss these in more detail.

#### *Dissipative (D)*

The dissipative extreme is characterised by having a wide, shallow surf zone over which energy is dissipative. Breakers are commonly between 2.0-3.0 m and break 200-500 m seaward of the shoreline, depending on the breaking wave height. Small bars are often present across the surf zone which is characterised by spilling breakers. On the inner bar-terrace, breakers are spilling-plunging (Fulton, 1991). The surf scaling parameter ( $\epsilon$ )  $>20$ , Dean's parameter ( $\Omega$ )  $>6$  (see 5.2.2 and 5.2.3). Sediment is fine sand.

#### *Longshore bar-trough (LBT)*

The Longshore Bar-Trough consists of a bar and trough that are parallel to the shore. Breakers are characteristically 1.5-2.0 m and are plunging in nature over the bar. Weak to moderate rip currents form. The swash zone is more reflective and the limited dissipation produces infragravity standing wave circulation. Associated edge waves impose weak rip circulation (Short, 1979b). Sediment is fine to medium sand.

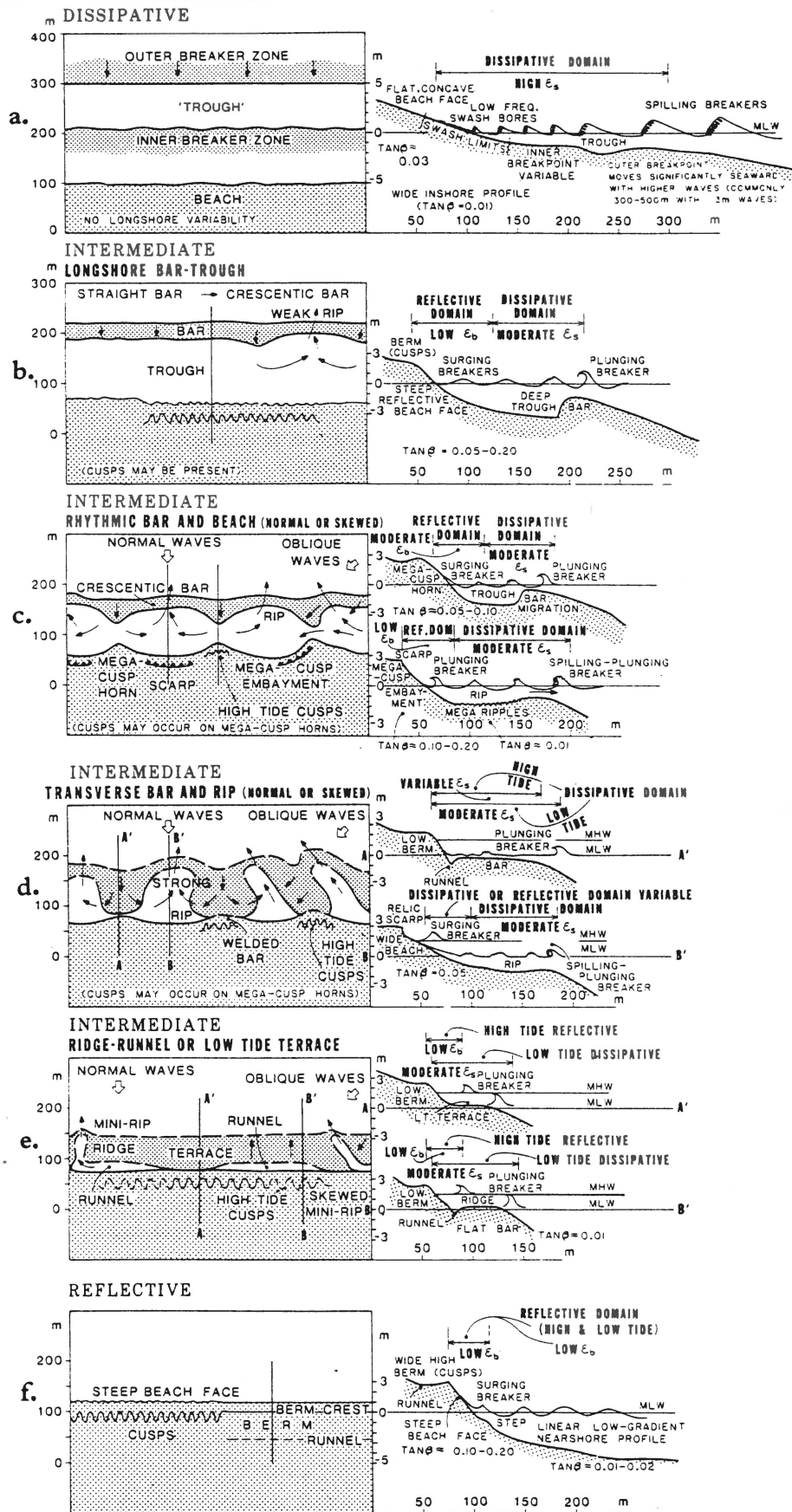


Fig. 5.1 Major beach states of the Wright and Short beach state classification system

*Rhythmic bar and beach (RBB)*

RBB is characterised by rhythmic bar and trough and a straight beach consisting of fine to medium sand. Waves plunge over the bar at low tide with moderate-strong rips every 150-300m. In the trough there is alternation between being shallow with onshore currents to deeper with pulsating rip feeder and rip currents. In the swash zone there are lower waves and shallow water behind the bars and deep water and feeder currents behind the rips.

*Transverse bar and rip (TBR)*

The TBR beach state consists of attached bars, rip troughs and undulating beach with fine to medium sand. Rip troughs exist, separated by attached bars every 150-300m. The bars are welded and are transverse to the shore and alternate with deeper rip troughs and currents. In the swash zone, there are low waves in lee of the bars and a steeper beach and a low shorebreak in lee of rips. In this state, rip circulation is at it's strongest. Breakers are commonly 1.0-1.5 m in height.

*Ridge and runnel or Low tide terrace (LTT)*

Consists of a shallow bar-terrace exposed at the low tide mark. The beach consists of fine to medium sand and conditions are characterised by 0.5-1.0 m waves. Over the bar the breaking waves are plunging in shallow water. The swash zone is moderately steep, reflective conditions causing waves to surge and producing high tide cusps.

*Reflective*

The breaking wave height on a reflective beach is less than 1.0 m and the waves tend to reflect back off the beach. Sediment is medium to coarse sand. The high tide zone is often characterised as having beach cusps. There is no bar or trough and the swash zone is steep.  $\epsilon > 2.5$ ,  $\Omega > 1.0$ .

The beach states represent a transition from high energy, erosional events through to low energy, accretionary events. This process is accompanied by a decrease in the surf scaling parameter and the surf zone width. The most erosive state is the dissipative extreme. As

energy decreases, a LBT state develops and the shoreward crest of the bar divides the profile into a reflective domain and a highly dissipative outer domain. As the bar welds onto the beach, the dissipative properties also move onshore and a RBB system develops. This stage has longshore and shore-normal separation of dissipative and reflective sub-systems. More dissipative regions grow at expense of the reflective regions as transverse and anvil-shaped bars of the TBR system develop. The shoals widen into the broad form of the LTT beach state and the beach becomes reflective at high tide and dissipative at low tide. The low tide shoals can climb onto the subaerial beach, the surf scaling parameter lowers and the beach becomes fully reflective.

### 5.2.2. Surf scaling parameter

The extreme states of the model, reflective and dissipative conditions, are distinguished using the surf scaling parameter. This parameter was first proposed by Guza and Inman (1975) whilst studying the formation of beach cusps and edge waves in regard to reflectivity of beach systems. The parameter can be considered as a measure of the degree of reflectivity. The parameter is dimensionless and is given as:

$$\epsilon = a_b \frac{2\pi}{T} / (g \tan^2 \beta), \quad 5.1$$

where  $a_b$  is breaker amplitude,  $\beta$  is the beach or inshore slope ( $^\circ$ ),  $T$  is wave period (s),  $g$  is the acceleration of gravity ( $m/s^2$ ) (Wright and Short, 1983).

The boundary values for the reflective and dissipative states were established as  $\epsilon \leq 2.5$  and  $\epsilon > 20.0$  respectively (Short and Wright, 1984). Complete reflection occurs when  $\epsilon < 1.0$  but Guza and Bowen (1977) and Guza and Inman (1975) note that as long as  $\epsilon < 2.0$  to 2.5 strong reflection will occur and permits strong standing wave motion, surging breakers, and resonance (especially at subharmonic frequencies). When  $\epsilon < 2.5$ , waves begin to plunge, dissipating energy and when  $\epsilon > 20.0$ , spilling breakers occur. With increasing  $\epsilon$  values the surf zone widens and there is an increase in the dissipation of incident wave energy. The intermediate states are in the range between the two extremes.

### 5.2.3 Fall Velocity Parameter

Wright and Short (1984) state that beach state is a function of breaker height, period and sediment size. The fall velocity parameter ( $\Omega$ ) provides a means to include these parameters in a dimensionless form given as:

$$\Omega = \frac{H_b}{(\omega_s T)} \quad 5.2$$

where  $H_b$  is the breaker height (m),  $\omega_s$  is the mean sediment fall velocity (m/s) and  $T$  is wave period (s) (Dean, 1973).

The fall velocity parameter was introduced to the model so that all six beach states can be distinguished. It is also used in the prediction of beach state as the prevailing  $\Omega$  indicates the beach state which the beach will reach if the prevailing wave and sediment characteristics persist long enough. It does not necessarily indicate the prevailing beach state (Wright *et. al.* 1984).

Wright and Short (1984) analysed 11 Australian beaches to determine threshold values for  $\Omega$  transition from dissipative to intermediate systems and for reflective to the intermediate beach states.  $\Omega$  is less than 1.0 for a beach to be reflective and greater than 6.0 for a dissipative system. Intermediate beach states fall between these two values.

Table 5.1 Classifications of beach state (Fulton,1991) (Source-Wright and Short, 1983 and Wright *et. al.*, 1984).

Beach type	Beach state	$\epsilon$	Hb	$\Omega e$
Dissipative	Dissipative	> 20.0	>2.5	> 5.5
Intermediate	Longshore bar trough	20.0	2.0-2.5	4.70-0.93
	Rhythmic bar and beach			3.50-0.76
	Transverse bar and rip			3.15-0.64
	Ridge and runnel	2.5	1.0-1.5	2.40-0.19
Reflective	Reflective	<2.5	<1.0	< 1.5

The six beach states of the Wright and Short model are listed in Table 5.1, along with the surf scaling parameter and Dean's parameter that are used to distinguish between the beach states.

The Surf scaling parameter and Dean's parameter calculated for the eastern Coromandel beaches investigated are presented in Table 5.2.

Table 5.2 Surf scaling parameter ( $\epsilon$ ), Dean's parameter ( $\Omega_h$ =horn,  $\Omega_e$ =embayment) and the fall velocities ( $\omega_h$ =horn,  $\omega_e$ =embayment) for the investigated eastern Coromandel beaches (Those sediment samples that were too coarse to be put through the RSA do not have fall velocity values so the Dean's parameter cannot be calculated).

Beach	Date	$\epsilon$	$\omega_h$ (m/s)	$\omega_e$ (m/s)	$\Omega_h$	$\Omega_e$
Buffalo	3/91	3.5		0.065		1.09
Buffalo	4/91	2.72		0.081		0.55
Buffalo	7/92	8.32		0.099		0.67
Buffalo	11/91	4.25/10.55				
Cooks	5/92	2.41	0.041	0.036	0.93	1.05
Hahei	5/92	1.04	0.047	0.047	1.12	1.12
Hahei	8/92	0.96	0.049	0.049	0.89	1.08
Kuaotunu	3/91	1.81		0.043		0.68
Mara	7/92	2.10	0.091	0.065	1.02	1.50
Mara	8/92	0.25	0.093	0.069	0.12	0.16
Mara.	3/92	0.63	0.101	0.060	0.35	0.58
Mara.	5/92	1.45	0.061	0.092	0.72	1.08
Rings	3/91	0.53	0.069	0.049	0.43	0.41
Rings	3/92	0.89	0.079	0.079	0.63	0.76
Rings	5/92	0.60	0.095	0.086	0.33	0.38
Rings	8/92	1.00	0.058	0.058	0.71	0.77
Wharekaho	5/92	0.64	0.060	0.045	0.91	1.19
Wharekaho	7/92	1.26	0.069	0.051	1.28	1.74

### 5.3 Morphological beach state and the occurrence of beach cusps

Wright *et. al.* (1982) states that beach state is associated with subharmonic and infragravity edge waves. He suggests that morphology changes drastically according to whether the incident wave is strongly reflected or propagates shoreward as a dissipative bore. Short (1979b) states that there can be significant standing wave-energy over the full range of morphological conditions but reflectivity is thought necessary for the occurrence of subharmonic edge waves and beach cusps are commonly observed on those beaches with strongly reflected incident wave (Guza and Inman, 1975; Guza and Bowen, 1977). Subharmonic edge waves occur on reflective beaches and are thought to initiate and control the spacing of beach cusps (Guza and Inman, 1975; Huntley and Bowen, 1975a). Longer infragravity waves can be excited by more dissipative systems.

Wright *et. al.* (1982) states that edge waves can form if certain morphological conditions are met. The edge wave frequencies, mode numbers and lengths which may prevail under a given set of incident wave and morphological conditions depends on (Wright *et. al.* 1982):

1. The ability of the system to reflect the energy necessary to maintain the standing wave situation.
2. The ability of the forcing waves to overcome viscous damping and transfer energy to edge waves.
3. The degree to which resonance is damped by dissipation.
4. The ability of the inshore system to accommodate edge waves of a certain length.

These factors depend on the slope of the beach and the wave energy reaching the beach.

### 5.4 Energy changes and morphological adjustment

As previously stated, the Wright and Short model represents changes in beach morphology in response to changes in wave energy.

Short term beach change is a function of changes in wave energy. Bars migrate onshore and offshore depending on wave conditions. Interactions between migrating bars and the wave and current fields gives rise to characteristic beach morphology changes (Horikawa, 1988). Bar movement and beach topography changes have been investigated by Sonu (1973) and Short (1979b).

The beach states delineated by Wright and Short (1983) show a transition from high energy conditions (the dissipative extreme) through to low energy conditions (the reflective extreme). Offshore bars migrate onshore as energy decreases. Such a bar was observed at Buffalo Beach at a time when the beach was devoid of beach cusps. Komar (1986) says that bars form during storm conditions and migrate shoreward under the influence of subsequent low-energy swell waves. If these calm conditions prevail for long enough then the ridge welds onto the back beach and builds a berm under swash-backswash action. Their mobility is a function of the wide ranging wave conditions and the continuous alterations from storm to swell profile.

#### **5.4.1 Buffalo Beach (11/91)**

Buffalo Beach was monitored for period of 10 days to investigate accretionary and erosional events associated with cusp development. No cusp development was recorded but decreasing wave energy caused the onshore migration of an offshore bar. The beach was monitored using a grid of nylon cords. The grid consisted of 5 profiles, each 5.0 m apart. Each profile extended from the low tide mark onto the low tide terrace. Each profile had nine cords extending through the intertidal beach at 2.5 m intervals. The cords were buried approximately 1.0 m into the sediment and the length of the exposed cord was measured by pulling the cord tight against a wooden metre rule. An increase in the length of the exposed cord indicated erosion and a decrease indicated accretion. This method appeared accurate to 1.0 cm assuming that the cord was not tampered with. The cords were measured at low tide of each day. On the last day of the monitoring period, the cords were surveyed using a theodolite to establish a datum against which fluctuations could be monitored. The daily profiles could then be plotted to determine erosion and accretion.

Wave approach was consistently normal to the shore, the breaking wave height was small for most of the measured period ranging from flat conditions to a maximum height of 0.8 m,



Fig. 5.2 Ridge and Runnel Beach state on Buffalo Beach (11/91) showing the migrating bar cut by regular channels.



Fig. 5.3 Reflected incident wave moving seaward over the bar at Buffalo Beach (11/91).

averaging 0.2-0.3 m. The swell period was 9.0 seconds. The surf zone was narrow, waves breaking on the beach, over the step and being of a plunging type. At low tide the surf zone increased in width to 1.0-2.0 m. The wind was consistently offshore, from the southwest and because of these prevailing weather conditions, there was no significant swell from the east entering Mercury Bay.

The beach state was similar to that of the ridge and runnel system described by Wright and Short (1983) (Fig. 5.2). The beach face ( $\beta=4.0^\circ$ ) was steeper than the low tide terrace ( $\beta=1.0^\circ$ ). The bar was cut by relatively regular channels. At high tide, when the bar was overtopped by swash, the backwash was concentrated in the channels and flowed seaward. The beach face was relatively reflective having a  $\epsilon$  value of 4.25 and the low tide terrace had an  $\epsilon$  value of 10.55 indicating more dissipative conditions. Fig. 5.3 shows incident waves being reflected from the beach face (at high tide) and travelling seaward over the bar.

The bar of the ridge and runnel system was observed to move over the low tide terrace. The distance migrated was recorded each day. This migration is shown diagrammatically in Fig. 5.4. At the height of migration the bar moved 22.0 m in 24 hours. Sonu (1968) recorded bar movement of 29.3 m per day at Nags Head in North Carolina and Sallenger (1985) observed migration of 28.8 m per day during the DUCK experiment. Figure 5.5 illustrates the movement of the bar at Buffalo Beach over the low tide terrace and the accretion of sediment on the beach face.

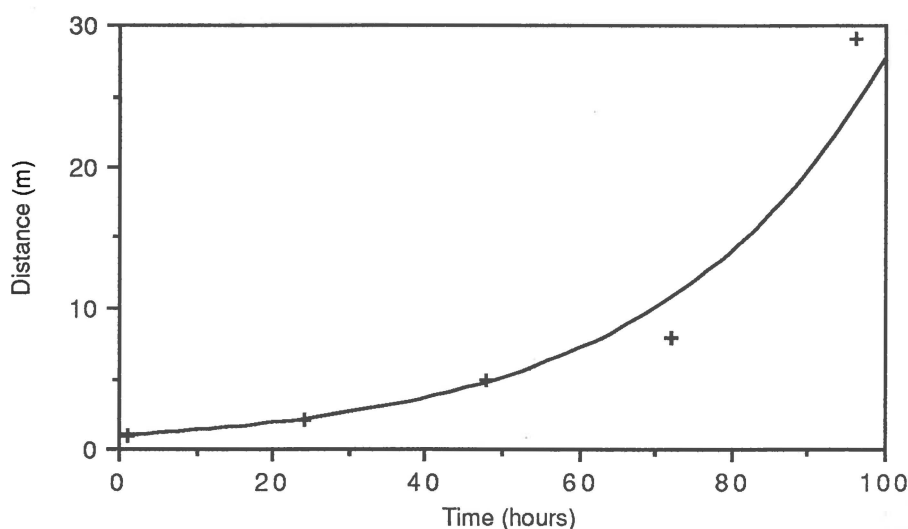


Fig. 5.4 Graph of bar migration over time.

Once the ridge and runnel system reached the change in slope between the beach face and the low tide terrace, shoreward migration ceased. This is in agreement with Sonu's (1972) observations, stating that the landward migration of swash bars ceases as it reaches the limit of swash run-up. The bar flattened and spread laterally, the runnel outlet channels becoming less pronounced as the amount of water overtopping the bar decreases. Even when the bar welded to the beach face, sediment continued to move onto the beach with 15.0-20.0 cm of sediment accumulating in 48 hours (on top of what had previously accumulated during the bar migration).

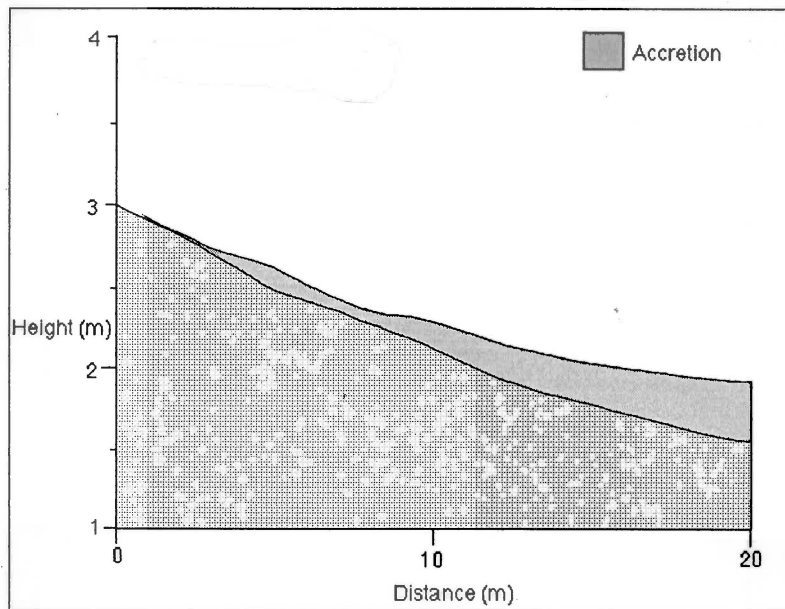


Fig. 5.5 Accretion of the beach face during the migration of the bar as measured with the cord grid system (after 9 days).

## 5.5 Discussion

In terms of the surf scaling parameter ( $\epsilon$ ), Buffalo Beach was the most dissipative with  $\epsilon$  values ranging from 2.72-10.55. The other beaches ranged from 0.25-2.41 and varied depending on the beach and conditions at the time. All beaches (except Buffalo Beach) had  $\epsilon$  values less than 2.5 which indicates that wave reflection from the beach could occur and permit standing wave motion. Those beaches with values less than 1.0 could have total reflection of wave energy from the shoreline.

For the Dean's parameter ( $\Omega$ ), two values are shown in Table 5.2 as the fall velocity for the horn and embayment samples were used. Table 5.1 shows that reflective beaches have values

$\Omega$  less than 1.5 which encompasses all the beaches investigated. As the Dean's parameter can be used as a predictor of beach state, it can be suggested that under the prevailing wave conditions the ridge and runnel/low tide terrace systems of Buffalo Beach would become more reflective if the conditions prevailed for long enough.

Visual observations of beach morphology concur with that of a reflective beach state in Wright and Shorts model. The beaches investigated in this study (except Buffalo Beach) consisted of a steep linear beach face. At the base of the beach face was a coarse step, seaward of the step the beach gradient decreased rapidly. At high tide, the waves broke over the step and surged onto the beach face. At low tide, the surf zone was wider due to the less steep nature of the lower beach and waves broke further offshore.

Wave data from Chapter Three illustrates that the breaking wave height was consistently less than 1.0 m in agreement with typical wave energy for the reflective extreme (Table 5.1). Wave type data from Chapter Three shows that waves were surging except for at Buffalo Beach where they were more plunging in nature. Buffalo Beach had more dissipative elements than the others, having a wider surf zone where the waves broke further offshore. Because Buffalo is a less reflective system, this may account for cusps occurring relatively infrequently on the beach.

From the morphological characteristics of the beaches, in terms of the Wright and Short beach state classification, all beaches can be considered to be reflective except for Buffalo Beach which had morphology more characteristic of a ridge and runnel/low tide terrace system.

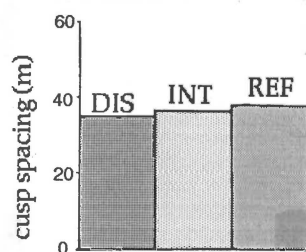


Fig. 5.6 Mean spacing of cusps in relation to beach states at Ibeno Beach (Antia, 1987).

Antia (1987) found that mean cusp spacing increased with increased reflectivity (Fig. 5.6) of beach state on Ibeno Beach, Nigeria and also found that cusps were more regular in spacing on the more reflective beaches.

Figures 5.7 and 5.8 graph reflectivity (surf scaling parameter) against cusp spacing and cusp regularity for eastern Coromandel beaches. Fig. 5.7 has a correlation coefficient of 0.728 which is in agreement with Antia (1987) results suggesting there is a relationship between cusp spacing and the degree of beach reflectivity.

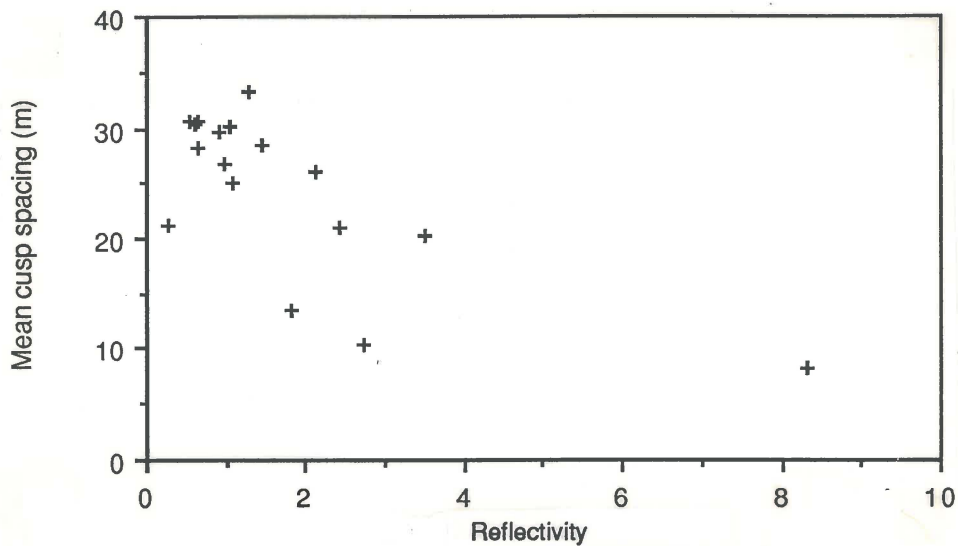


Fig. 5.7 Reflectivity ( $\epsilon$ ) plotted against mean cusp spacing for eastern Coromandel beaches ( $r=0.728$ ).

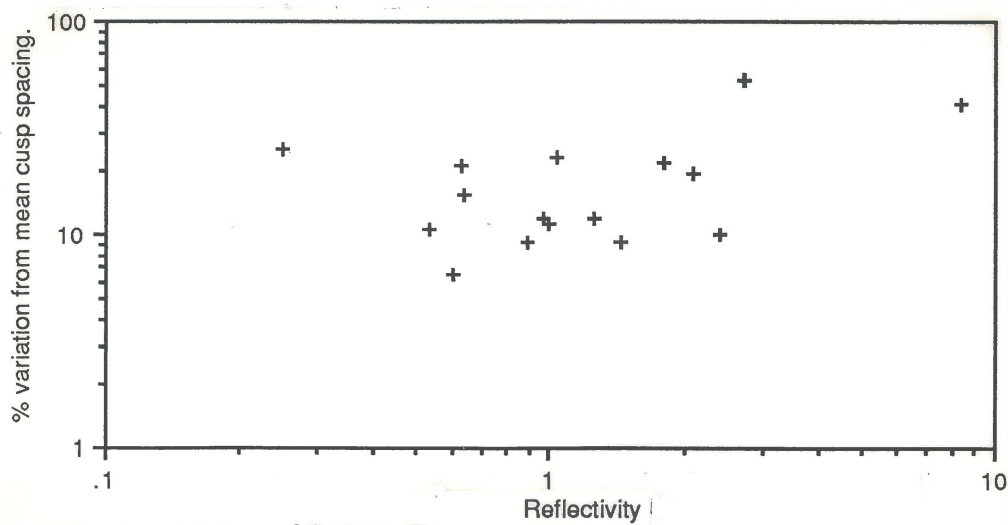


Fig. 5.8 Reflectivity versus cusp regularity (the % variation from the mean cusp spacing) for the investigated beaches ( $r=0.576$ ).

Antia (1989) found a high correlation between reflectivity and the standard deviation from the mean cusp spacing indicating that cusps require high stability in environmental conditions in order to exist or persist. Fig. 5.8 has a correlation coefficient of 0.576 indicating a general increase in beach reflectivity results in more regularly spaced cusps, as suggested by Antia (1989).

Data taken from Antia (1987) graphed in Fig 5.9 shows that cusps were most widespread or stable in occurrence on the reflective segments of the beaches whereas they were transient on the dissipative segments. As previously discussed in Chapter Three, cusps on some beaches were more persistent and lasted longer and occurred more frequently than others. Looking at reflectivity values those beaches that consistently have cusps (eg. Ring and Maramaratotara Beaches) are more reflective than those beaches that are not consistently cusped (eg. Cooks and Buffalo Beaches).

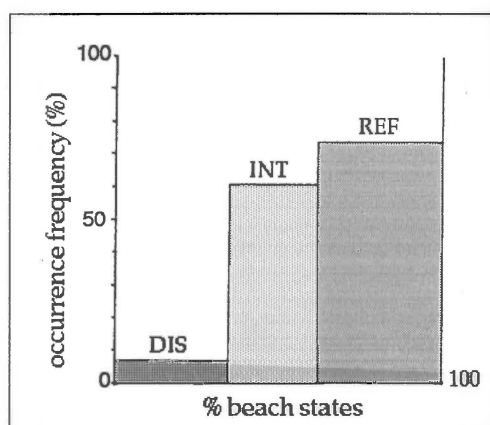


Fig. 5.9 Cusp occurrence as a function of spatial distribution in modal beach states at Ibeno Beach (Antia, 1987).

In terms of the migration of a bar during low energy conditions at Buffalo Beach, this appears to be a precursor to cusp formation. Wright *et. al.* (1984) state during the transition from a ridge and runnel system to a reflective beach state, rip channels infill as the bar migrates and welds onto the beach face. The beach face steepens and cusps are deposited. It appears what was observed was the transition to a reflective beach state with changes in topography in response. Sallenger (1979) observed a similar occurrence where a ridge migrated and was accreted onto the foreshore. The channels were eroded on the ebb tide resulting in a cusped shape. Sallenger (1979) states that there must still be sufficient energy for the bar to be cut into cusped features. Sallenger found that the spatial distribution of beach cusps was

dependent on wave energy. Along a beach of changing wave energy, he found that cusps occurred at the highest energy section and a ridge and runnel system where wave energy was lowest with transitional features at an intermediate wave energy level. Sallenger's observations showed a clear progressive longshore change in morphology along the length of a beach corresponding to wave energy changes. He attributed these longshore wave energy changes to wave refraction. Wave refraction, energy changes and the spatial distribution of cusps is investigated in Chapter Seven.

## 5.6 Conclusion

The Wright and Short model of beach classification appears to account for beach morphology at the beaches investigated accurately.

All of the beaches, except Buffalo Beach, showed morphological features consistent with reflective beaches, further supported by the surf scaling parameter and Dean's parameter. Buffalo Beach was more characteristic of a ridge and runnel system. Fulton (1991) points out that the Wright and Short model is based on the microtidal environment of the southeastern and southern Australian beaches that are characterised by a persistent swell regime. The wave climate on the eastern Coromandel is more variable where waves heights are predominantly under 1.0 m but can be over 4.0 m during episodic easterly storms. The beaches on the Coromandel have a micro to meso tidal range. Fulton (1991) suggests that these differences result in some beach states that are not recognised in the Wright and Short model. However, in this investigation, observations concur closely with beach states described by the model.

Beach cusps formed under reflective conditions where the beach face slope was steep and the waves were surging and were reflected from the beach face. Cusps didn't form on Buffalo Beach when the beach was less reflective and the waves were plunging in nature. The migration of a bar cut by channels at Buffalo Beach appeared to be a pre-cursor to cusp formation and represented accretion of the beach and the transition to a more reflective beach state which may have been more conducive to cusp formation. Observations of beach state and bar migration concur with the observations of Sallenger (1979).

The reflective and dissipative distinction manifests itself in the associated resonant waves as well as in the beach morphology. Wright and Short (1984) state that as well as having a characteristic morphology, reflective beaches have characteristic nearshore wave spectra. In the following chapter, current meter data and spectral analysis is used to investigate the wave spectra at two of the beaches to assess whether it is characteristic of the beach morphological state and to investigate if the nearshore hydrodynamics can be related to edge waves and beach cusps.

## *Chapter Six*

### *Nearshore wave spectra characteristics of cusped and non-cusped beaches on the eastern Coromandel*

#### **6.1 Introduction**

From Chapter Five, it can be concluded that the beaches investigated are toward the reflective end of Wright and Short's beach state classification spectrum, being either reflective or ridge and runnel systems and have a morphology characteristic of these beach states. Chapter Four illustrated that edge waves could theoretically exist on these beaches which concurs with the observations of previous investigations of reflective beaches (Short, 1979; Short and Wright, 1983; Wright *et. al.*, 1982a; Wright and Short 1984 ).

Wright and Short (1984) state that reflective beaches have characteristic nearshore wave spectra dominated by resonance at subharmonic frequencies that is indicative of edge waves.

This chapter analyses the process signatures associated with the hydrodynamics of two Coromandel Peninsula beaches. Rings Beaches (3/92) was cusped, Buffalo Beach (2/92) was not. The spectra are analysed and compared to spectra from Wright (1982) and assessed to determine whether it is typical of the beach states observed. Whether the hydrodynamics can be related to cusped morphology is also investigated.

#### **6.2 Spectral analysis**

The ocean consists of a complex mix of different wave types travelling in different directions. The addition of these different waves results in a sea surface similar to that shown in Fig. 6.1.

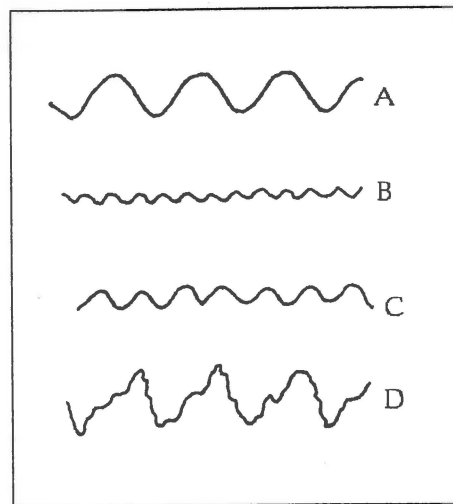


Fig. 6.1 The addition of simple sine curves (a, b, c) add to give the more complex form of d, representative of sea waves (Pethick, 1984).

Spectral analysis interprets the wave spectrum by breaking it down into its constituent wave forms. Thus, the individual wave types present in the wave spectrum can be determined. The data is usually presented as a graph of the energy present at each frequency (Hz) or period (s) in the spectrum.

To investigate the wave processes on the two beaches, the following analysis procedure was used:

1. A S4 current meter (Fig. 6.2) was deployed in the nearshore zone at each of the beaches. It was attached to a concrete slab at 1.0 m above the sea bed. The S4 current meter measured and stored data of the horizontal current direction and velocities. The current meter recorded data in bursts, each burst being 35 minutes long with a 5 minute non-recording time between bursts. The S4 sampled at 0.5 s intervals.
2. The data was downloaded onto the Toshiba 5200/100 using InterOcean software.
3. The data was written to text files using the InterOcean S4 package.
4. The program S4REFORM (provided by Dr. Willem De Lange, Earth Science Dept., University of Waikato) on the Toshiba T2500/100 was used to extract the individual data

bursts. Each data burst consisted of onshore-offshore ( $u$ ) and longshore ( $v$ ) velocity components and depth ( $\eta$ ) (representative of wave height) data.



Fig. 6.2 The S4 current meter

5. A representative burst of data from each beach was used in the program S4FFT (provided by Dr. Willem De Lange) which undertakes a spectral analysis of the data within the burst. A Boxcar window was applied to the raw data. The output consisted of the spectral density for each frequency for the  $u$ ,  $v$  and  $\eta$  data.

6. S4FFT was used to produce a time series from portions of the spectra. Infragravity and capillary wave frequencies were removed (0.0-0.05 and 0.25-1.0 Hz) to leave the incident wave data. To investigate infragravity energy, incident wave and capillary wave energy was removed (0.0-0.125 and 0.05-1.0 Hz).

7. The data were transferred from the Toshiba (MSDOS) to the Apple Macintosh system.
8. The data were manipulated using Cricket Graph<sup>®</sup> (via Word 4.0<sup>®</sup>) as the data were a text file) and hardcopies of the spectral analysis and time series were obtained.

### 6.2.1 Resonant processes - Buffalo Beach (2/92)

An experiment was carried out in on the 28th February 1992, (for a period of four hours) at Buffalo Beach to investigate the spectral characteristics associated with a non-cusped beach. The breaking wave height was 0.5-0.8 m with a wave period of 7.5 s (estimated from the beach). The wave approach angle was directly onshore and the waves were plunging at the break point. The surf zone was approximately 10 m wide. There were no cusps present and no indication of any offshore bars although no surf zone transect was surveyed. The experiment was conducted on a rising tide, two hours before high tide. The current meter was deployed approximately 30 m from the shore.

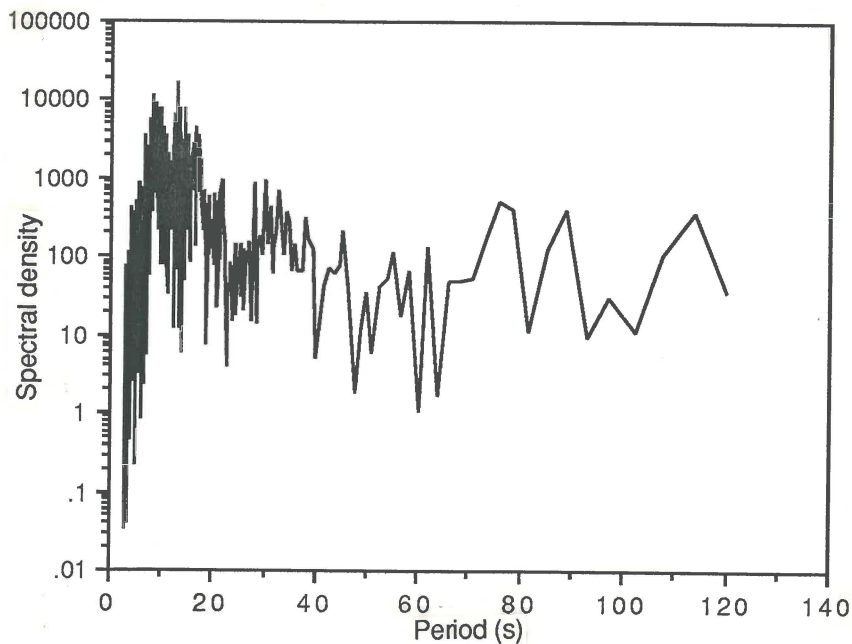


Figure 6.3. Typical depth spectra measured by the S4 current meter in the nearshore zone at Buffalo Beach (2/92).

A typical power spectrum of depth data is shown in Fig. 6.3. The spectrum illustrates dominant energy centred between 8.0 - 18.0 s. Two significant spectral peaks are evident, the first centred around 8.0-10.0 s and is indicative of locally generated wind waves. The second spectral peak is centred around 14.0-16.0 s and is representative of the swell wave period. The wave period estimated visually from the beach is less than the swell period spectral peak because of the addition of the wind and swell waves in the estimation. Although most energy is at incident wave frequencies, there are secondary peaks at infragravity frequencies.

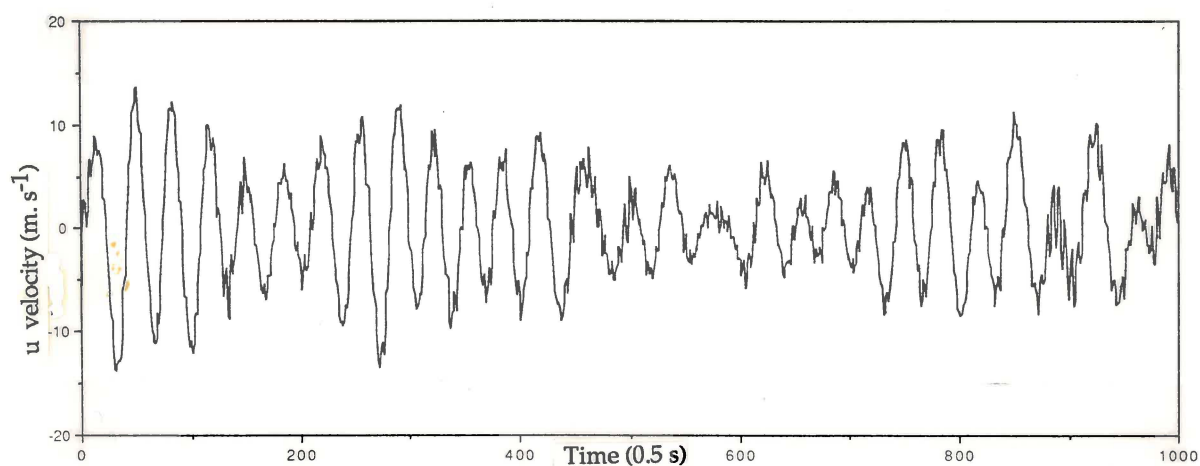


Figure 6.4a Time series of the incident onshore-offshore ( $u$ ) velocity component of the nearshore velocity field at Buffalo Beach.

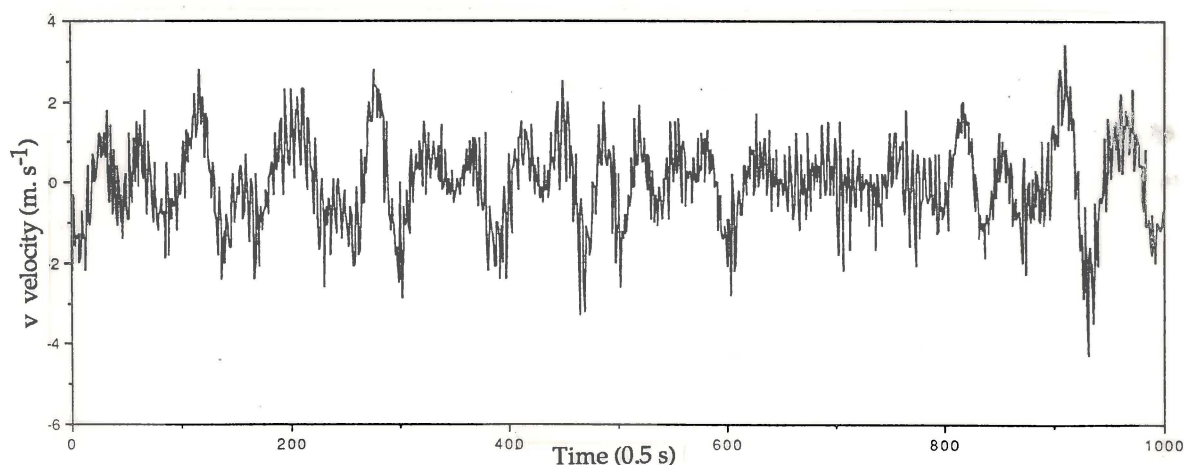


Figure 6.4b Time series of the incident alongshore ( $v$ ) velocity component of the nearshore velocity field at Buffalo Beach.

A time series of the nearshore wave spectrum from Buffalo Beach was recreated using the S4FFT program to look at energy at incident and infragravity frequencies in more detail.

Initially, long period and capillary wave frequencies were filtered out to leave incident wave frequencies (Fig 6.4 a, b and c). The data illustrate periodicity corresponding to a swell wave period of approximately 16.0s. The  $v$  (alongshore) data are noisier and considerably weaker although does show a similar trend. These plots illustrate that the dominant motion is at incident wave frequencies. The depth ( $\eta$ ) data show wave heights between 20.0 and 60.0 cm, similar to what was estimated from the beach.

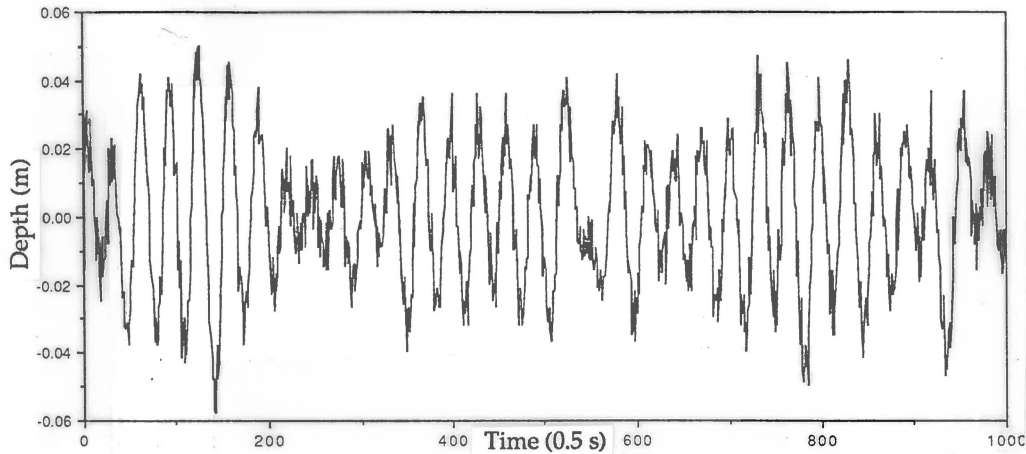


Figure 6.4c Time series of the depth ( $\eta$ ) component of the nearshore velocity field at Buffalo Beach.

Fig. 6.4c illustrates well the variation in wave height - waves increasing in height and then being reduced in height which is indicative of wave groupiness. A similar, but weaker periodicity is also evident in the onshore-offshore ( $u$ ) time series.

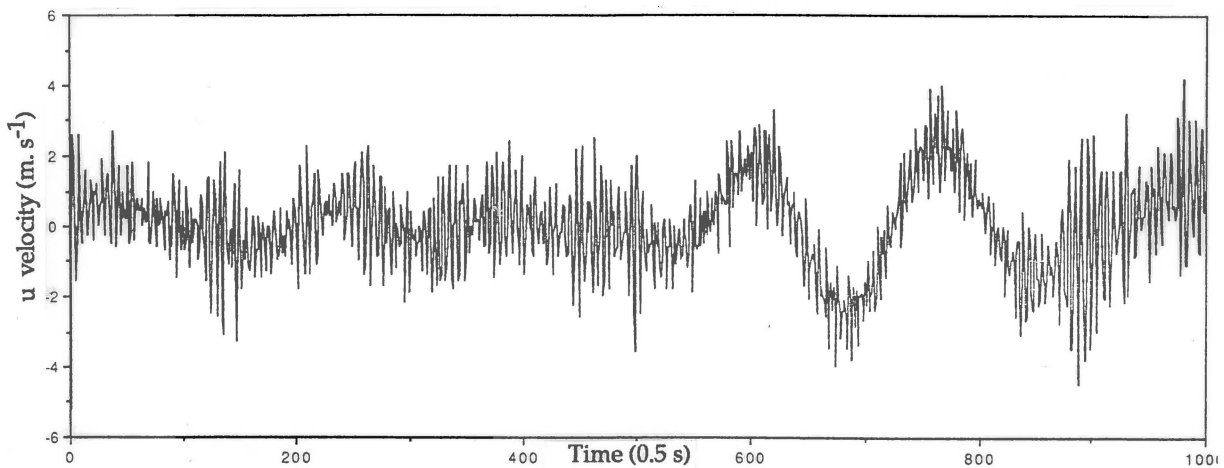


Figure 6.5a Time series of the infragravity ( $u$ ) onshore-offshore velocity component of the nearshore velocity field at Buffalo Beach.

Oscillation is also evident at infragravity frequencies where the incident and capillary frequencies have been filtered out (Fig 6.5 a, b and c). The oscillation shows a periodicity of

approximately 60.0-80.0 s which falls into the lower infragravity range of 'surf-beat' ( $T=80-150$  s). This oscillation at infragravity frequencies is evident in the depth ( $\eta$ ) and alongshore ( $v$ ) time series data and to a lesser extent in the offshore-onshore ( $u$ ) data. The wave heights of this longer period wave motion is less than incident wave motion being between 10.0-20.0 cm. Velocities are greatly reduced in comparison to the incident wave velocities.

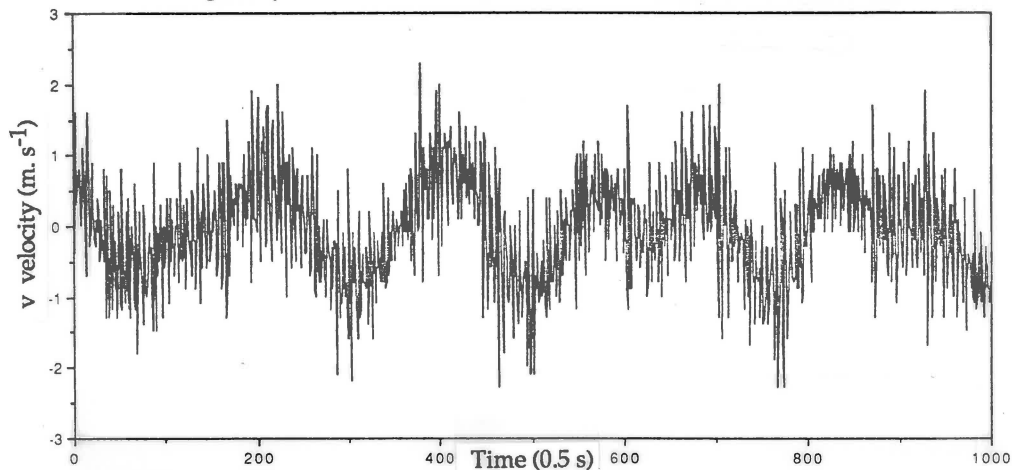


Figure 6.5b Time series of the infragravity ( $v$ ) alongshore velocity component of the nearshore velocity field at Buffalo Beach.

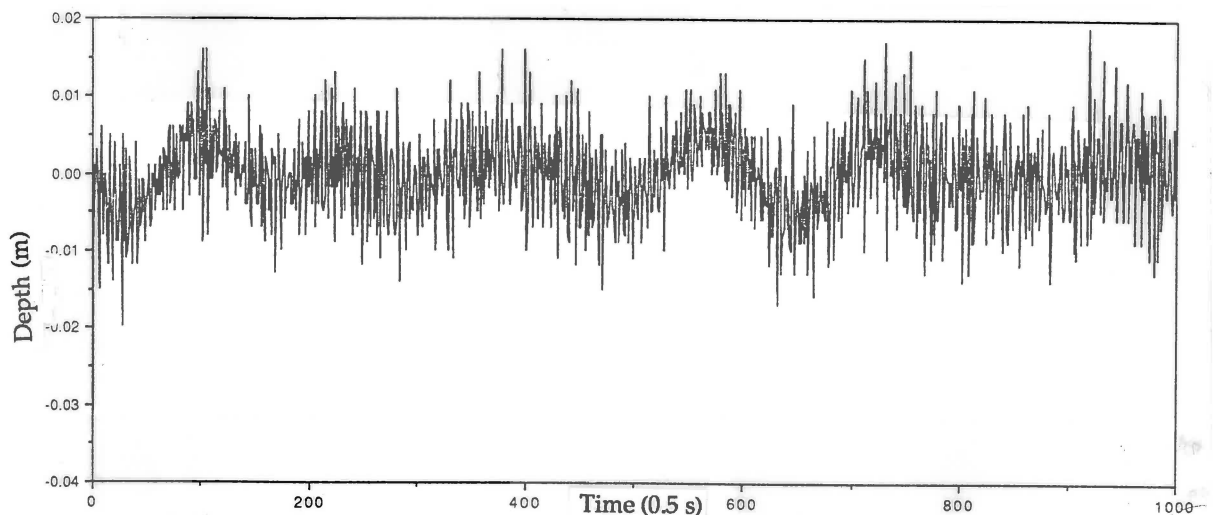


Figure 6.5c Time series of the infragravity ( $\eta$ ) depth component of the nearshore velocity field at Buffalo Beach.

### 6.2.2 Resonant processes- Rings Beach (3/92)

An S4 current meter was deployed at Rings Beach March of 1992 for a period of 4 hours to investigate the spectral characteristics of a cusped beach.

Wave conditions were estimated from the beach and the breaking wave height was 0.3-0.4 m with an 11.0 s period. The wave approach was onshore and the waves broke directly on the

beach and surged up the beach face. There were no bars visually evident. Cusps were present at the eastern end of the beach but decreased in development toward the western end until the cusp forms petered out. The mean beach face slope was  $6.5^\circ$ . The current meter was deployed in the cusped section of the beach approximately 30 m from shore.

The tide was rising and the current meter was deployed 2 hours before high tide. Conditions were calm and there was no significant wind.

Figure 6.6 shows a representative depth ( $\eta$ ) spectrum for Rings beach. The majority of the energy is centred at swell frequencies between 8.0-20.0 s. Two peaks are significant at these frequencies, one peak at 8.0s representing wind waves and two other peaks at 15.0 and 17.0 s indicative of swell waves.

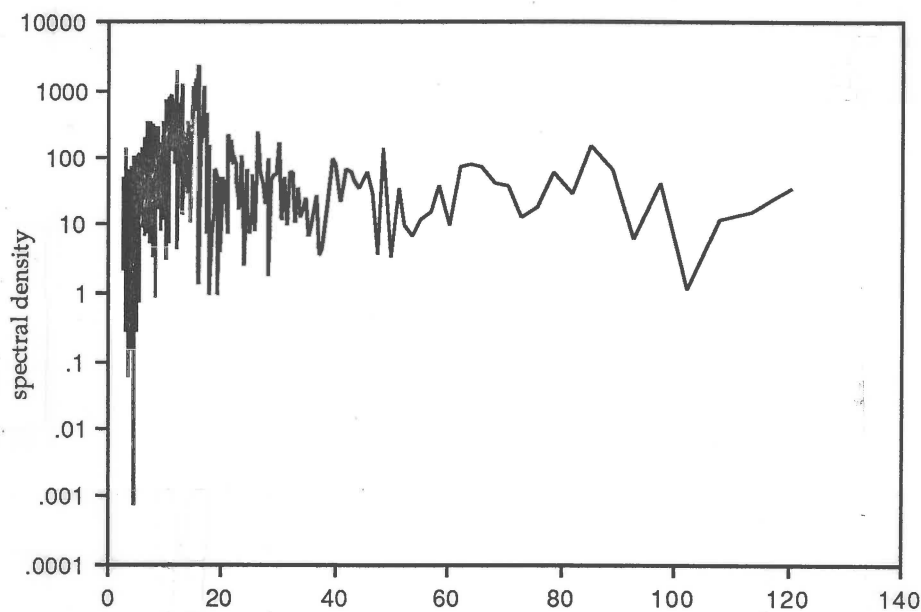


Fig. 6.6 Typical depth (representing wave height) spectra from the nearshore zone of cusped Rings Beach (3/92)

Figure 6.7 (a, b and c) shows time series of the  $u$  and  $v$  components of the nearshore velocity field and depth data at incident wave frequencies at Rings Beach. Fig. 6.7a indicates a distinct swell period of 16.0 s which is a longer period than was estimated from the beach. The  $v$  velocity component is less distinct than the  $u$  velocities but illustrates a periodicity of 14.0 s. Comparison of the onshore-offshore average velocities ( $u=18.0$  cm/s) and the longshore velocities ( $v=8.0$  cm/s) indicates that the dominant motion at incident wave frequencies is

predominantly onshore-offshore motion. The depth time series shows two peaks thought to be induced by the current meter and irrelevant to actual water motion. The depth time series indicates small wave heights at incident wave periods between 10.0 and 20.0cm.

Considerable wave groupiness is evident in the onshore-offshore time series data where groups of larger wave heights are followed by groups of smaller waves. A similar groupiness is evident in the depth data but the trend is not as strong.

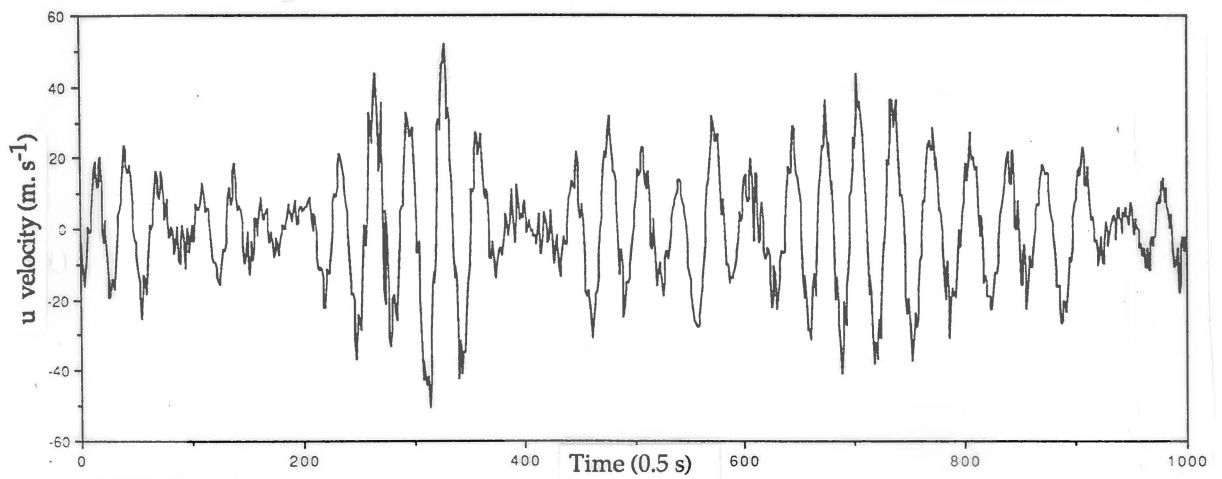


Fig 6.7a Time series of the onshore-offshore ( $u$ ) velocity component of the nearshore velocity field at incident wave frequencies on Rings Beach.

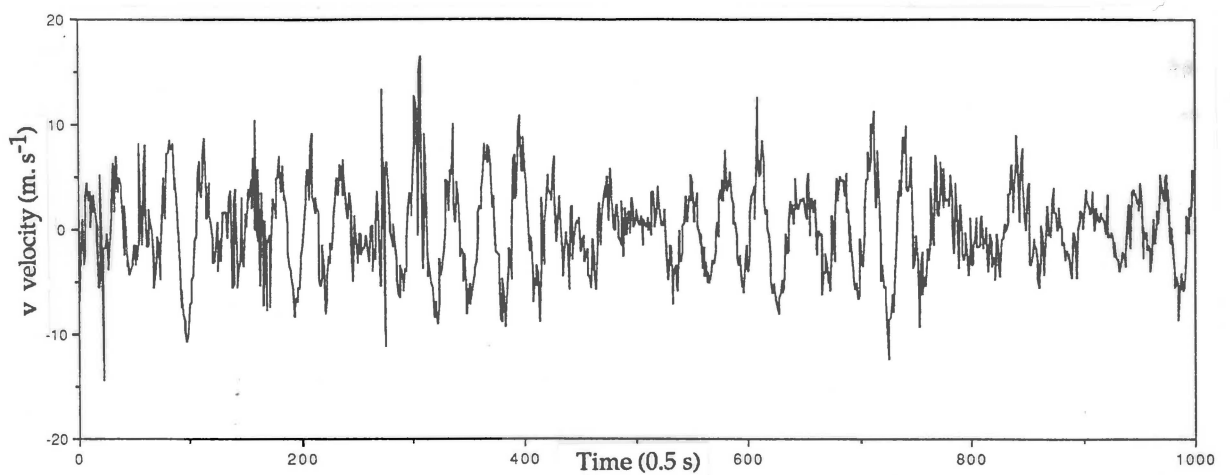


Fig 6.7b Time series of the alongshore velocity component ( $v$ ) of the nearshore velocity field at incident wave frequencies at Rings Beach.

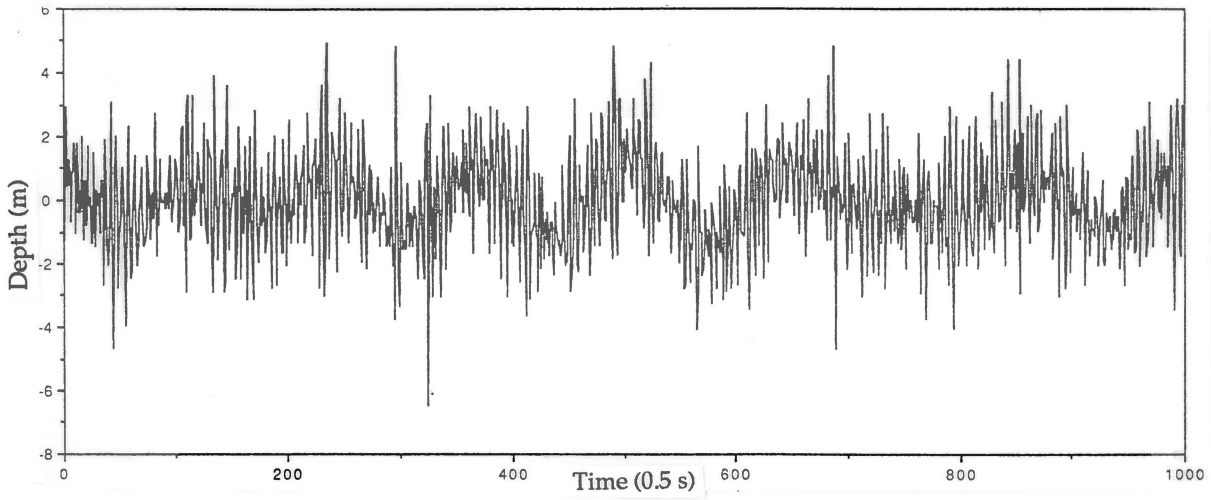


Fig 6.7c Time series of depth ( $\eta$ ) values at incident wave frequencies.

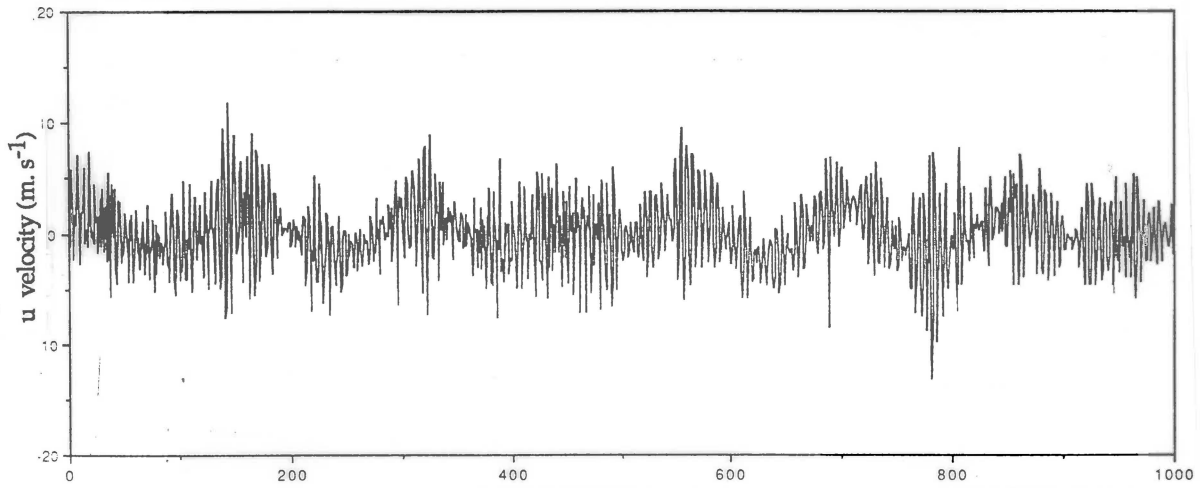


Fig 6.8a Time series of onshore-offshore ( $u$ ) velocity component of the nearshore velocity field at infragravity frequencies at Rings Beach.

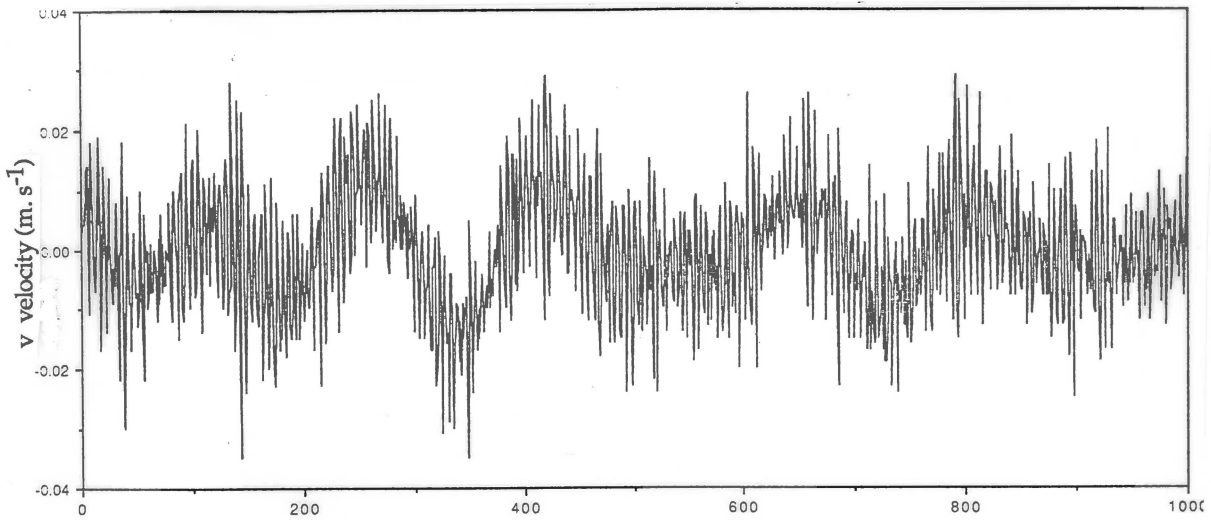


Fig 6.8b Time series of alongshore ( $v$ ) velocity component of the nearshore velocity field at infragravity frequencies on Rings Beach.

Incident and capillary frequencies were filtered out to leave wave motion at infragravity frequencies (Fig. 6.8 a, b and c). The  $v$  and  $\eta$  time series show oscillations at infragravity frequencies ranging between 60.0-80.0s. This is not so obvious in the  $u$  time series.

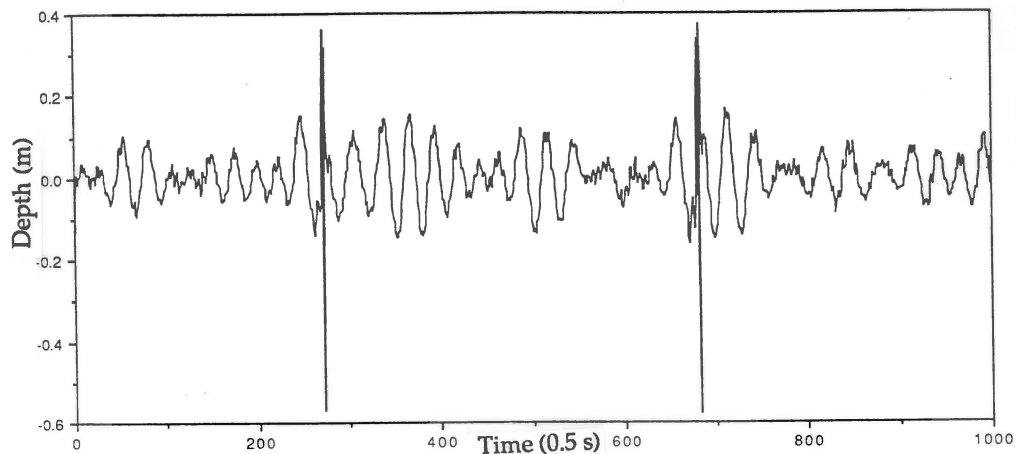


Fig 6.8c Time series of depth ( $\eta$ ) values at infragravity frequencies on Rings Beach.

### 6.3 Discussion

Fig. 6.9 illustrates typical wave spectra from a reflective beach (Wright, 1982). Wright (1982) notes that the most important characteristic of a reflective beach is an incident wave spectral peak and an additional spectral peak at the first subharmonic of the incident wave period. The spectra from both Rings and Buffalo Beach do not exhibit this subharmonic spectral peak suggesting that the spectra for both beaches is not typical of a reflective beach (note that the published data from Wright (1982) moves from low frequencies to high frequencies along the y axis whereas the data from the eastern Coromandel moves from high frequencies to low frequencies along the y axis).

Evident in the incident frequency time series from Buffalo and Rings Beach is pronounced wave groupiness or 'surf-beat' - where waves grow in height and then decrease in height. Surf-beat is the result of two long period swell waves whose frequencies are slightly out of phase. The addition of these waves creates a series of higher waves followed by a series of lower waves (Fig. 6.10). This sets up rhythmic vibrations in the nearshore which can have important morphological implications for the nearshore zone (Pethick, 1984).

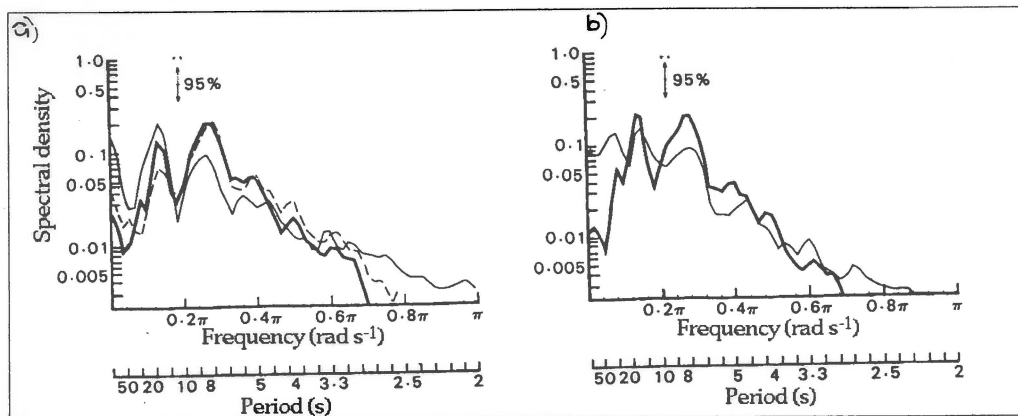


Fig. 6.9 power spectra for a reflective beach system (Bracken Beach, Australia); a) depth spectra, — outer station, - - - - mid station, — inner station; b) onshore-offshore data, — mid station, — inner station (Wright, 1982).

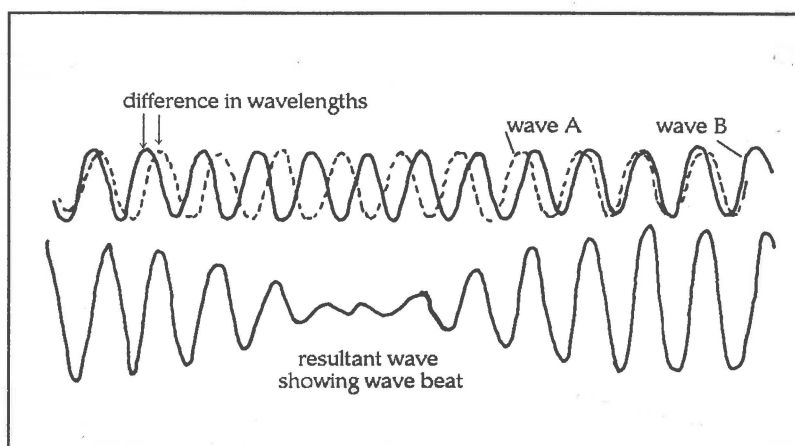


Fig. 6.10 The addition of waves with slightly different periods resulting in surf-beat fluctuations (Pethick, 1984).

Lonquet-Higgins and Parkin (1964) and Symonds *et. al.* (1982) suggest that low frequency fluctuations associated with groupy wave trains could possibly influence nearshore infragravity waves. They state that amplitude modulation of a groupy wave train forces a long wave through spatial and temporal variation in the radiation stress. Bowen and Inman (1969) agree, suggesting that the rhythmic beat of the incoming waves of the nearshore zone creates a secondary set of waves - edge waves. Lonquet-Higgins and Parkin (1964) state that 'surf-beat' is related to reflected long waves. Bowen and Guza (1978) suggest that 'surf-beat' is predominantly an edge wave phenomenon. The long period oscillations in the time series data from both Rings and Buffalo Beach correlate well with fluctuations in the incident wave data, indicating that the two are related as suggested by Lonquet-Higgins and Parkin (1964).

Figure 6.11 shows a hypothetical 'perfectly' grouped wave train (upper curve) and two natural time series (Wright *et. al.* 1987).

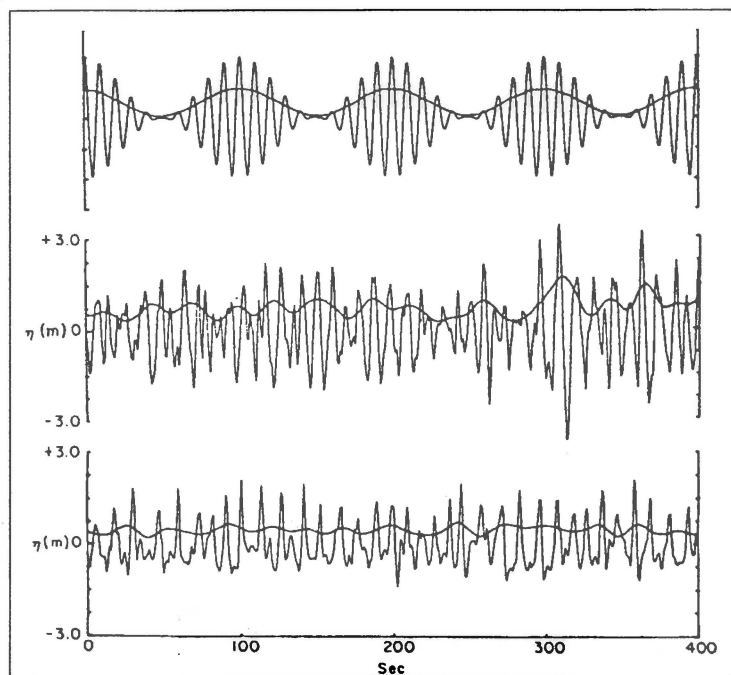


Fig. 6.11 The upper curve shows a hypothetical 'perfectly' grouped wave train. The lower two curves are two natural wave time series. The large displacement curves are the actual wave time series, the smoother low-amplitude curves represents the groupiness time series (obtained by the wave heights). (Wright *et. al.*, 1987).

Surf beat, as evident in the time series from Buffalo and Rings Beaches, is most commonly observed in the spectra of more dissipative beach systems. Figure 6.12 shows a typical spectra from a dissipative beach (Wright, 1982). Noted are no subharmonic peaks but a broad band of infragravity frequencies (particularly in the onshore-offshore (u) spectrum). The motion at surf-beat frequencies (Fig 6.12) was inferred by Wright (1982) to be 'leaky' mode infragravity standing waves or infragravity standing waves.

Fig. 6.13 illustrates typical spectra for a ridge and runnel system or transverse bar rip beach states (Wright, 1982). Energy is spread across the spectrum but with a dominant peak at incident wave frequencies. The spectra has energy at the subharmonic  $4T_i$  but this is only weak and is only evident at high tide. Energy is also present at the first subharmonic which was also more prominent at high tide.

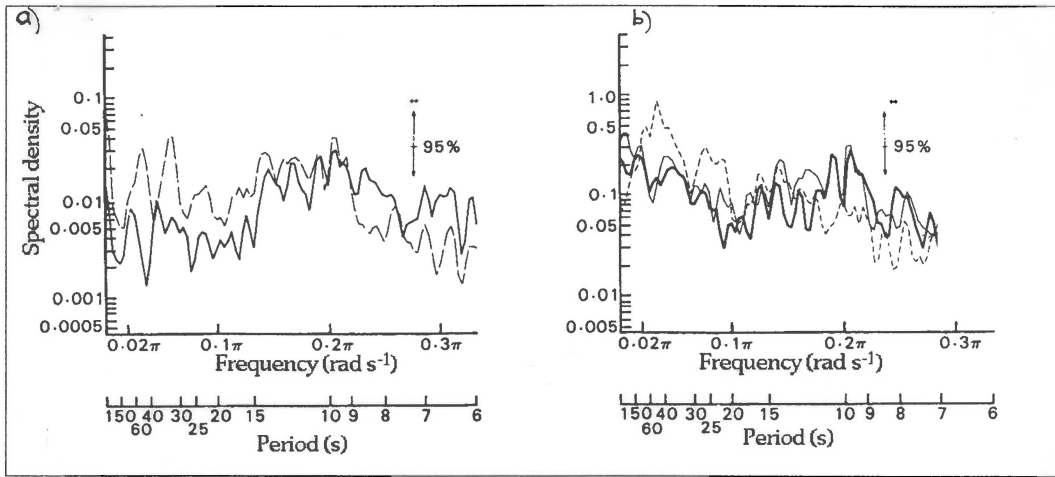


Fig. 6.12 Power spectra for a dissipative beach (Seven Mile Beach, Australia). a) depth spectra, ——— Outer station, - - - - inner bar (mid) station; b) onshore-offshore spectra, ——— outer station, ——— inner bar (mid) station, - - - - inner trough (inner) station (Wright, 1982).

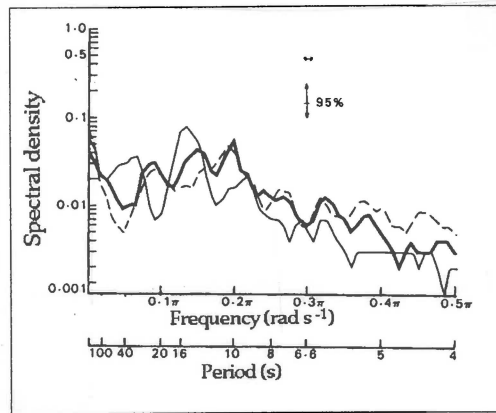


Fig. 6.13 Power spectra of an intermediate beach state (ridge and runnel/ transverse bar rip), depth and onshore-offshore data ——— U, outer station, ——— U, inner station, - - - - depth, inner station (Wright, 1982).

The spectra from both Rings and Buffalo Beaches compares well with Wright's (1982) spectra from the intermediate beach states, closer to the reflective end of the classification, exhibiting long period surf-beat oscillation but with most of the energy concentrated around the incident wave.

The evidence of wave groupiness and oscillation at low frequencies in both the Rings and Buffalo Beach data adds further support to the hypothesis that edge waves could form on the

beaches investigated. The 'surf -beat' oscillation may influence edge wave development and, in turn, initiate cusp development.

There is no energy at the first subharmonic of the incident wave that is thought to be typical of reflective beaches but the oscillation at 'surf-beat' frequencies may be indicative of energy at the 4th or 5th subharmonic. Referring to Ursell's (1952) equation (Chapter Four) that predicts the wavelength of an edge wave which can be used to predict the spacing of cusps, such long period edge waves correspond to edge wave wavelengths that are much greater than the dimensions of the cusps on Rings Beach and cusps that have observed to form in the past on Buffalo Beach.

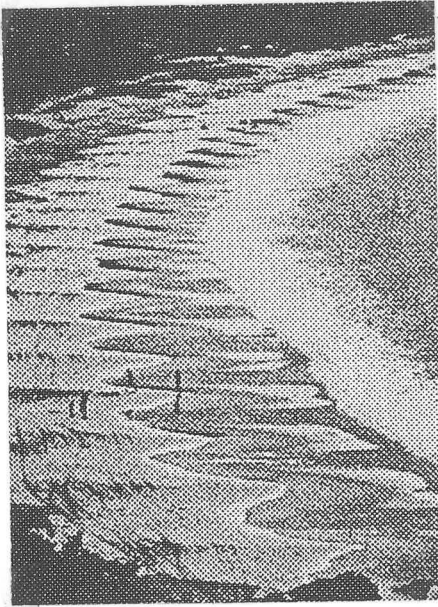
## 6.4 Conclusion

Although morphological observations indicated that Rings Beach is reflective and Buffalo Beach had a ridge and runnel/low tide terrace beach state, the spectra for both indicates that the spectra for both beaches is complex and contains both reflective and dissipative elements.

As the spectra from both Buffalo and Rings Beach was recorded on a rising tide, oscillations that may have been evident at high tide weren't visible in the spectrum.

There is some evidence for the existence of edge waves at the two beaches due to the wave groupiness evident in the spectra. Wave groupiness (or 'surf-beat') is thought to create and influence edge waves. With the limited data, these long period oscillations in wave height can not be related back to the cusped topography.

To better investigate long period oscillations, an array of current meters is needed to accurately measure the nearshore velocity field. Using an array of current meters, a longshore and offshore profile of wave motion can be gained.



## *Chapter Seven*

### *Wave refraction and the spatial distribution of beach cusps*

#### **7.1 Introduction**

Field observations reveal that beach cusp formation is often restricted to certain locations on an observed beach. This is evident at Buffalo Beach where cusps were observed to be limited to the southern end of the beach which is more reflective and characterised by higher wave energy than the northern end.

The amount of wave energy that impinges on a beach is a function wave height and swash excursion and this influences beach reflectivity and the degree of resonance along the beach. If these factors are thought to influence beach cusp formation, then changes in wave energy along the length of the beach may cause some locations (under the prevailing conditions) to be more suitable for cusp initiation.

Wave refraction analysis facilitates the simulation of wave climates on a given coast illustrating wave energy changes along that coastline. Swell and sea waves entering Mercury Bay are reduced due to refraction, diffraction and the shoaling of the sea bed (Smith, 1980). In this chapter, a wave refraction analysis is undertaken for Mercury Bay to investigate the concentration and distribution of wave energy within the bay. By comparing the results of this analysis with field observations of the spatial distribution of cusps, inferences can be made as to energy distribution along a beach and whether the longshore energy distribution can be related to cusp formation.

## 7.2 Wave prediction

Beach cusps on Mercury Bay beaches were observed and measured on the 28th and 29th of May, 1992. The distribution of these cusps on these beaches is depicted in Fig. 7.1. Local residents concluded that these cusps had formed a week earlier under higher energy conditions than the conditions at the time the cusps were measured. These conditions, related to cusp formation, could be predicted using the A.C.E.S (Automated Coastal Engineering System Wind) adjustment and wave growth program using wind direction, speed and duration.

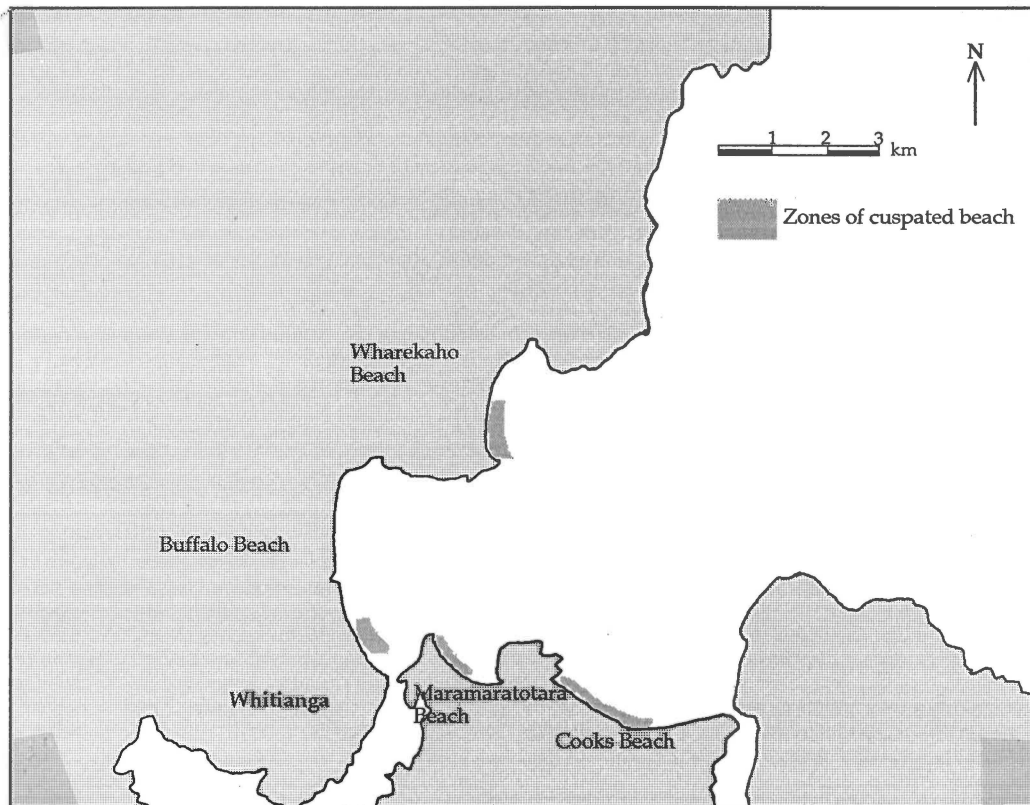


Fig. 7.1 Spatial distribution of beach cusps on Mercury Bay beaches observed in late May, 1992.

### 7.2.1 Wind direction.

Wind data was obtained for a four day period from Whitianga Airport. Wind directional changes are graphed in Fig. 7.2. It was illustrated in the time series observations of Chapter Three that cusps wind and waves from the easterly quarter are more conducive for cusp formation. The wind data shows easterly/northeasterly ( $0-90^\circ$ ) conditions on 23/5/92 (between hours 34 - 42 on Fig. 7.2) with a duration of 8 hours and it can be suggested that this was the time when cusp development was initiated.

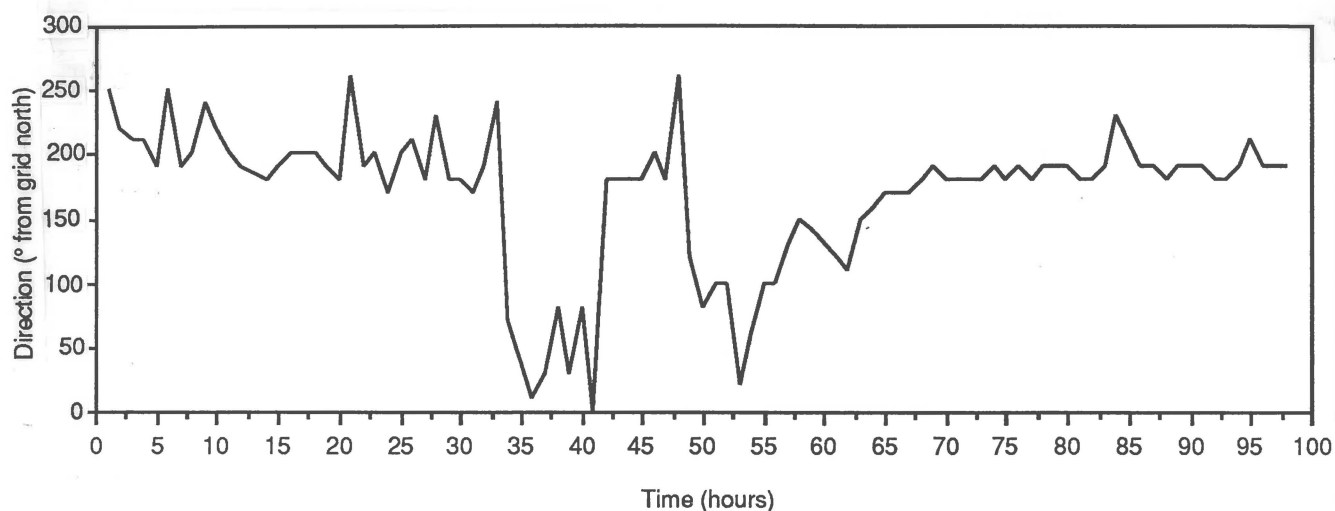


Figure 7.2 Wind speed directional changes as measured from the automated weather monitoring station at Whitianga Airport (22/5-26/5/92)

### 7.2.2 Wind speed calculation

The geostrophic wind speed (the free atmosphere wind above the level affected by surface friction) for the 8 hour northeasterly/easterly was calculated from the low pressure system illustrated from the weather map for Saturday (23/5/92) and Monday (25/5/92) (Figure 7.3). The velocity ( $V_g$ ) of the geostrophic wind is given by:

$$V_g = (1/2w \sin \phi \partial) dr/dr \quad 7.1$$

where  $w$ =the angular velocity of spin,  $\partial$  =air density,  $\phi$ =latitude and  $dr/dr$  =the pressure gradient.

This resulted in a geostrophic wind of 15knots at an altitude of 500 m.

### 7.2.3 A.C.E.S Windspeed adjustment and wave growth.

To ascertain the wave height and wave period that formed the cusps, hindcasting was carried out using the ACES (Automated Coastal Engineering System). This method of wave prediction estimates wave growth over open water and restricted fetches in deep and shallow water. It also adjusts observed wind speeds to those required by wave growth formulas. The geostrophic wind speed calculated from Eq. 7.1 and the wind direction determined from the weather forecasting map were used with deep water, open fetch input in the program.

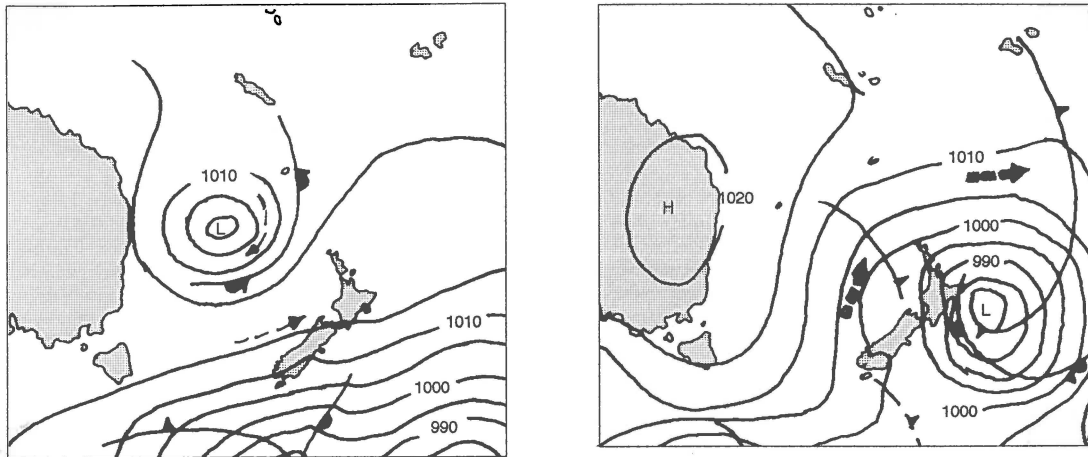


Fig. 7.3 Predicted weather conditions for 23/5-25/5/1992 (New Zealand Herald). On the 23rd, winds were from the northeast and were light but freshened through the day. On the 24th the wind was still from the northeast but was stronger. On the 25th winds were from the southerly quarter and by the 26th the southeasterlies were dying out.

The program calculated the parameters compiled in Table 7.1. The wave height and period are for deep water conditions situated in the entrance of Mercury Bay. This data was used in the wave refraction program to investigate refraction within the bay and to determine the relative breaking wave heights that formed the cusps at each beach.

Table 7.1 Wind adjustment and wave growth for Mercury Bay 23/5/92 (as predicted by the A.C.E.S wind adjustment and wave growth program).

Elevation of wind	Zobs	500 m
Observed wind speed	Uobs	15.0 knots
Air/sea temp. difference	delT	0.00 deg C
Duration of wind	DurO	8 hr
Duration of final wind	DurF	8 hr
Latitude	LAT	36.52 deg
Length of wind fetch	F	-
Equiv. neutral speed	Ue	7.14 knots
Adjusted wind speed	Ua	7.12 knots
Wave height	HmO	1.93 m
Wave period	Tp	5.48 sec
Wind direction	Wdir	42.00 deg
Mean wave direction	Theta	-

### 7.3 Wave refraction

Wave refraction results in deviations in the direction of wave travel so that the wave crests are parallel to the depth contours. As water depth decreases, the reduction in wave celerity causes a decrease in the speed of the wave crest so that the crest bends.

Snell's law can be applied to define the behaviour of waves where the change in direction is related to the phase velocity by:

$$\sin\alpha_1/C_1 = \sin\alpha_2/C_2 = \text{constant} \quad 4.2$$

where  $\alpha$  = the angle between a wave crest and a depth contour (Komar,1976).

Wave refraction affects wave energy and, consequently, wave height. This is because the refraction processes causes waves to diverge or converge. The orthogonals, which indicate the direction in which the wave is moving, show wave convergence or divergence. The energy flux between wave rays remains constant so regions of wave convergence are areas of energy concentration. Areas of divergence show a greater spread of energy (reference).

#### 7.3.1 Wave Refraction Analysis.

A bathymetric representation of Mercury Bay was constructed by Jones and Healy in 1988 by entering spot depths as data points into the wave refraction programme (Black and Healy, 1981). A coarse grid was constructed, consisting of grid squares 250 -250 m for initial wave refraction and a fine grid was devised (90-90 m grid squares) for more detailed examination.

Using the parameters specified (wave height, period and direction), the wave refraction programme - Refraction - (Black and Healy,1981) computes wave trains that travel across the bathymetric grid and are effected by changes in the bottom topography. As well as determining the wave propagation direction and orthogonal spacing, the program gives the wave height, the maximum orbital velocity and the maximum grain size moved. This information is derived from the orthogonal spacing indicating wave energy.

### 7.3.2 Limitations

Several restricting factors of the numerical wave simulation must be acknowledged:

The program assumes that all the waves are uniform whereas, in reality, a spectrum of varying waves reaches the shore.

Caustics occur when the bottom topography causes refraction to the degree that the wave orthogonals become tangential to each other so that the distance between them is zero. Wave height reaches infinity as the waves cross and the waves are assumed to break. The actual waves may not break and the concentration in wave energy in the area can effect the coastline. The residual energy after the wave has broken can effect the beach face and this is not taken into account in the program Black and Healy (1981).

The wave refraction analysis does not take into account the consequences of edge waves, seiching, rip currents (de Lange, 1988).

### 7.3.3 Wave diffraction

Smith (1980), as a result of refraction analysis, states that wave diffraction modifies the distribution of wave energy in Mercury Bay. Diffraction occurs in the lee of headlands resulting in the lateral dispersion of wave energy. This is most noticeable for Cooks Beach in the lee of the southern bay entrance headland, the northern ends of Buffalo and Wharekaho Beaches and in the lee of Shakespeare Cliff at the eastern end of Maramaratotara Beach.

### 7.3.4 Wind and wave climate

In Chapter Two, it was suggested that, for the northeastern coast, records show a significant wave height of 1.0 with wave periods ranging between 4.0 and 9.0 seconds (Pickrill and Mitchell, 1979). Smith (1980) investigated wave refraction within Mercury Bay using waves that were 1.0 m in height, and had periods of 10.0 s for swell waves and 7.0 s for sea waves. He states that such waves are representative of storm waves entering Mercury Bay.

As Mercury Bay has an easterly aspect, it is sheltered from the prevailing westerly conditions but is susceptible to easterly events. Storm generated sea waves are likely to enter the bay from the northeast and swing around to east during the passage of a storm. More northerly approach angles are prevented by sheltering from headlands and offshore islands.

The wave period (5.38 s) and wave height (1.93m) predicted by the A.C.E.S wave prediction program have been used for the wave refraction analysis and are considered representative of conditions within Mercury Bay.

#### **7.4 Wave focusing within Mercury Bay**

Wave refraction runs were started from three different angles, 45° (from grid north) simulating a northeasterly wave approach direction, 90° simulating an easterly wave direction and 135° simulating a southeasterly wave direction.

When the wave approach angle is from the northeast there is considerable wave focussing at some locations. Fig. 7.4 illustrates a concentration of wave energy at the southern end of Wharekaho Beach. This energy decreases to the north as indicated by the diverging wave trains. Motukorure Island causes a wave shadow zone on Buffalo Beach but to either side of the shadow zone are areas of wave convergence and higher wave energy. There is a zone of higher wave energy at the northern end at Maramaratotara Beach. Less wave energy reaches Cooks Beach, wave trains diverging along the length of the beach.

Similar trends are evident in Fig. 7.5 with a wave approach angle from the east although Cooks Beach is in a complete shadow zone due to the headland at the eastern end of the beach. More wave energy reaches Buffalo Beach as the sheltering effect of Motukorure Island is lessened. This is in agreement with Smith (1980) whose refraction analyses reveal a corridor of higher wave energies toward Buffalo Beach under similar conditions. The effects of refraction and diffraction along the southern side of this high energy corridor rapidly reduces wave energy toward Cooks Beach and south Buffalo Beach.

Smith (1980) notes that Motukorure Island, centred a short distance beyond the entrance of the bay, acts as a refractive lens which causes the formation of a shoreward extending caustic

envelope and a wave shadow zone of lower wave energy. This sheltering effect is evident in the wave refraction diagrams and causes the northern end of Buffalo Beach to be in a low energy envelope.

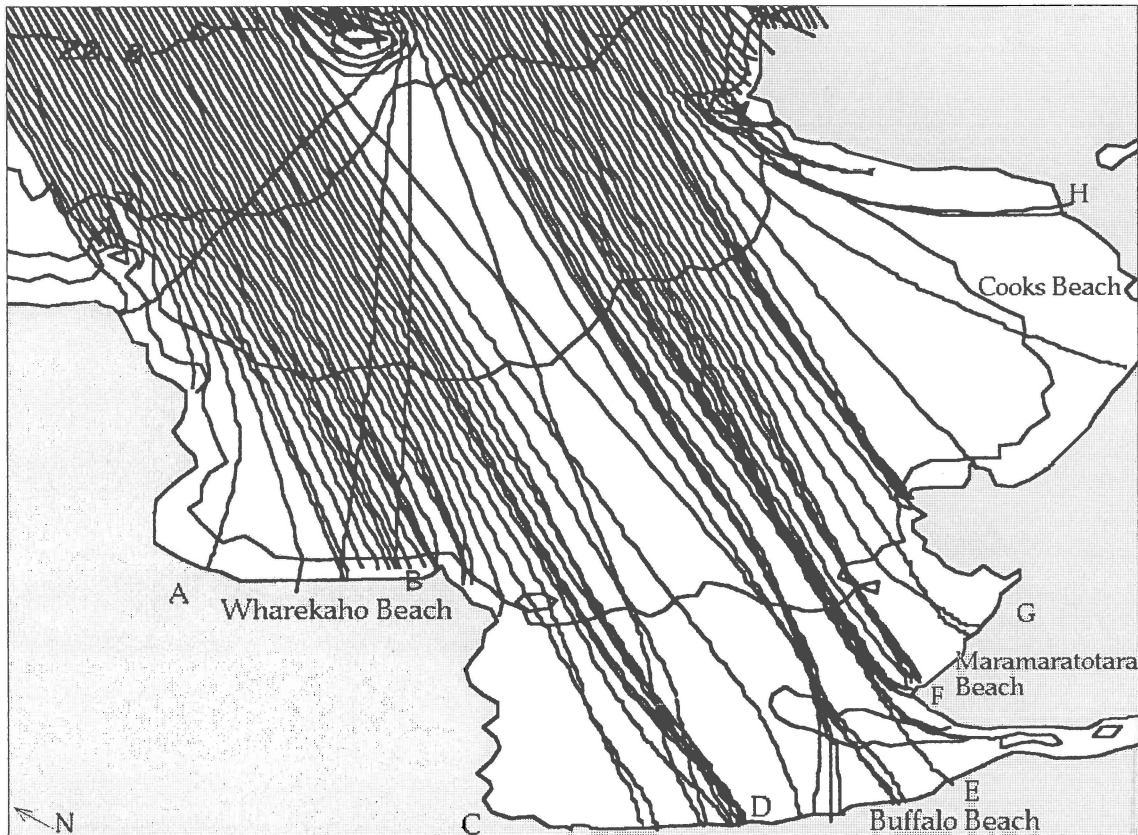


Figure 7.4 Zones of wave convergence and divergence within Mercury Bay ( $H=1.93$  m,  $T=5.48$ s, northeasterly wave approach angle). A illustrates diffraction of wave energy due the sheltering effect of the headland at the northern end of Wharekaho Beach. At B, energy is concentrated. From A to B, there is an increase in wave energy. Similar wave diffraction is shown at C on Buffalo Beach, this end of the beach having low wave energy. Wave energy is higher on the southern half of the beach with areas of wave convergence at several locations (D and E). Energy is concentrated at the western end of Maramaratotara Beach, energy decreasing to the east (G). Little wave energy reaches Cooks Beach under this wave approach angle with wave energy decreasing from G to H. I indicates the wave shadow zone caused by Motukorure Island.

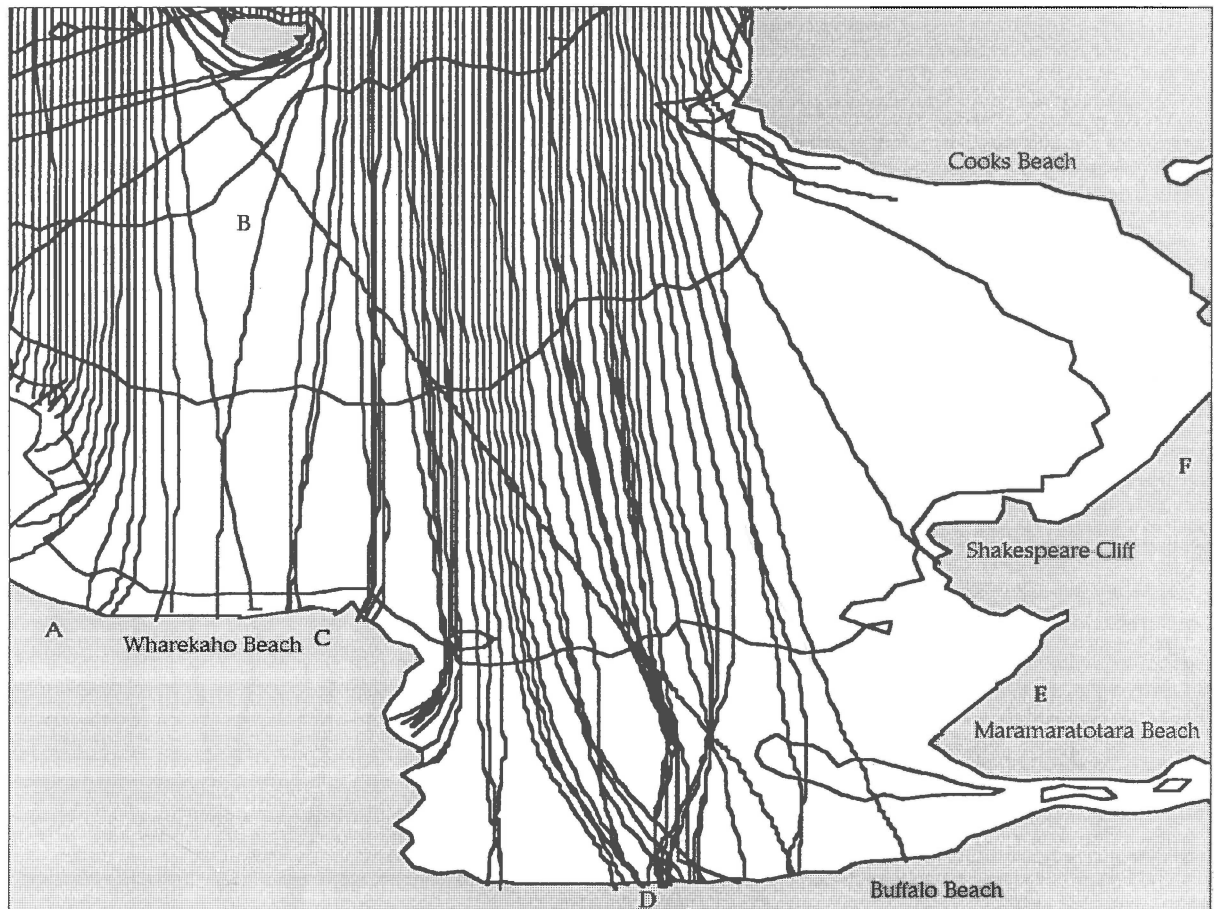


Figure 7.5 Zones of wave convergence and divergence within Mercury Bay ( $H=1.93$  m,  $T=5.48$  m, wave approach from the east). B illustrates the shoreward extending caustic envelope and wave shadow zone caused by Motukorure Island reducing wave energy impinging on Wharekaho Beach. Either side of the lower wave energy corridor are zones of higher wave energy (A and C). At Buffalo Beach there is considerable wave convergence in the centre of the beach (D). Maramaratotara and Cooks Beaches (E and F) are sheltered from direct easterly wave approach and energy is lower.

Waves from the southeast result in less energy entering Mercury Bay. There is considerable wave energy along the entire length of Wharekaho Beach and some convergence toward the centre of Buffalo Beach. Energy at Maramaratotara and Cooks Beach is significantly reduced.

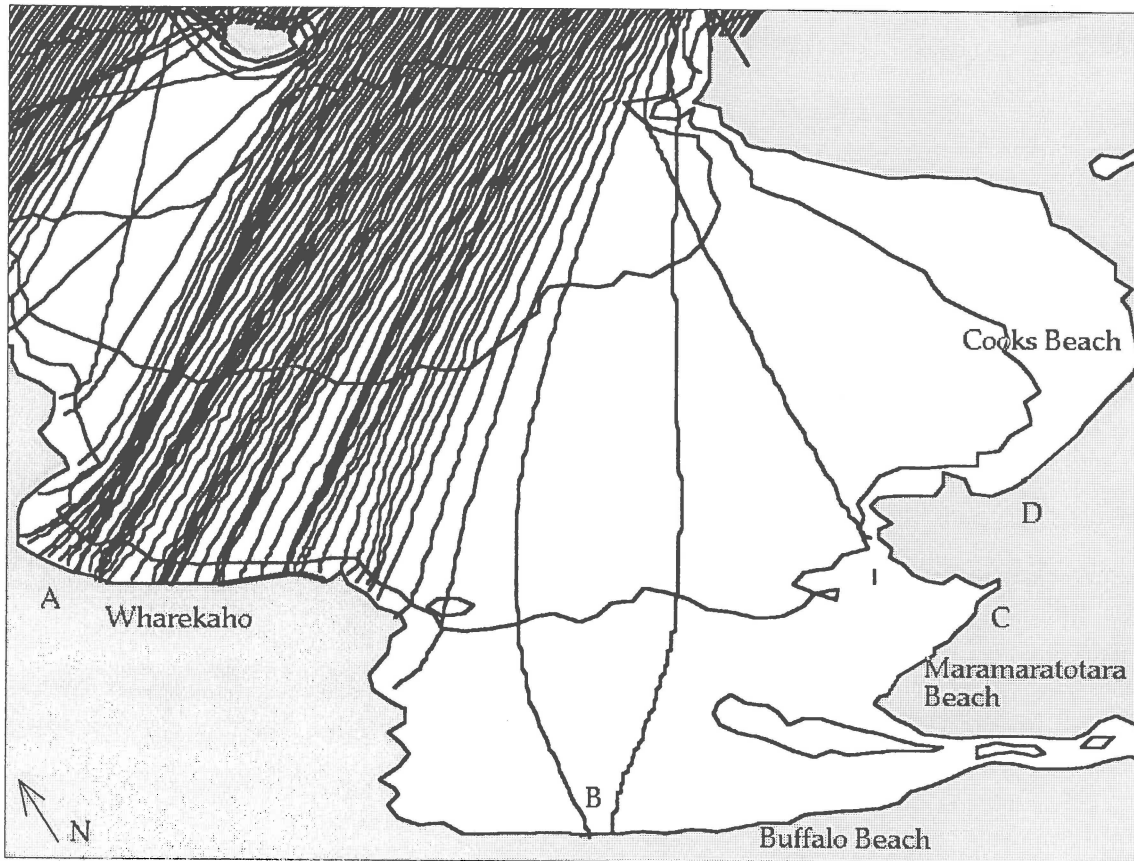


Figure 7.6 Zones of wave convergence and divergence within Mercury Bay. ( $H=1.93$ ,  $T=5.48$ , wave approach from the southeast). Under a southeasterly wave approach, considerable wave energy impinges on the entire length of Wharekaho Beach. Wave energy is reduced on the other beaches of Mercury Bay. There is some wave convergence in the centre of Buffalo Beach (B). Wave heights on Maramaratotara and Cooks beach (C and D) are smaller relative to Wharekaho Beach.

### 7.5 Wave refraction, diffraction and beach cusp occurrence

It is evident that wave refraction and diffraction influences the alongshore distribution of wave energy in the nearshore zone of Mercury Bay beaches. Under the northeasterly conditions, shown by the wind data of Fig. 7.2, there appears to be a strong correlation between areas of wave focussing and the spatial distribution of cusps on the beaches within Mercury Bay. The beach cusps appear to form on the beaches where the energy levels are higher relative to other longshore locations.

Of interest is the observation that from the wave refraction diagrams, energy on Wharekaho Beach appears to be the most consistent, with considerable wave energy impinging on the southern end of Wharekaho Beach in all conditions northeasterlies. Wave energy on Buffalo Beach is more variable and areas of convergence and divergence vary with wave approach angle. Wave energy is less than Wharekaho Beach. Maramaratotara and Cooks beaches are more susceptible when the wave approach is from the north or northeast and are sheltered from easterlies and southeasterlies. Energy impinging on Cooks Beach is less than at Maramaratotara Beach. This distribution of energy is in agreement with earlier observations in Chapter Three where it was concluded that Wharekaho receives more wave energy than Buffalo and Maramaratotara which both have higher energy than Cooks Beach.

It appears that cusps occur, on the beaches investigated within Mercury Bay, where wave focusing occurs and wave energy is higher. From Chapter Three, it was shown that beach slope appears to be the dominant parameter associated with the spacing and spatial distribution of beach cusps. It was also shown that steeper beaches are associated with higher wave energy and, from Chapter Four, that steeper beaches are more reflective and therefore more likely to develop resonance at infragravity frequencies (possibly edge waves). It can therefore be hypothesized that if wave energy changes along a beach, this will result in changes in beach slope, cusps forming on the steeper sections of the beach.

Considering edge wave theory and the application of the theory to beach cusps, the theoretical maximum and minimum wave height for subharmonic excitation (Eq. 4.7 and 4.8 respectively) can be applied. The variation in wave height along the beach may indicate that where waves diverge, there may be insufficient energy for edge wave excitation or insufficient energy for edge wave motion to extract enough energy from the incident wave to cause the initiation of beach cusps. At higher energy areas of the beach, there may be sufficient energy for edge wave motion to have a dominance on the nearshore sediment processes (up to the theoretical maximum wave height, Eq. 4.7, which differs from beach to beach) and form beach cusps on that region of the beach.

## 7.6 Conclusion

Wave refraction analysis indicates that the beaches of Mercury Bay are exposed to swell waves from the northeast through to the southeast.

Refraction and diffraction of wave energy appears to result in longshore variation in wave height. The areas of wave convergence (higher energy) correspond to areas of cusp development while at locations of wave divergence (lower energy) cusps are absent or less developed (in terms of the vertical distance between the cusp horn and the cusp embayment).

It can be suggested that the longshore spatial variation in wave height can influence the spatial distribution of beach cusps. Wave refraction analysis suggests that areas of a beach where energy is higher and the beachface is steeper are more conducive to cusp formation.



## *Chapter Eight*

### *Conclusions*

#### 8.1 Summary

The primary objective of this study was to investigate beach cusps on seven eastern Coromandel Peninsula beaches in terms of their sedimentological, morphodynamic and hydrodynamic properties. The beaches investigated differed in terms of aspect, beach length and slope, sediment size and wave climate but several common parameters and processes that are associated with beach cusps were identified at these beaches and these interrelationships are discussed in the following.

Field observations of beach cusps indicate that it is the action of swash that forms and maintains the cusped topography. The interaction of the swash excursion and the coarse, permeable sediment of the cusp horn and the finer, less permeable sediment of the cusp embayment results in liquefaction at regular longshore intervals (at the base of each cusp horn) at the water table-beach interface. The wave breaks on the coarse step, and the swash easily entrains this liquefied coarse sediment and it is transported up the beach face where it is deposited as the swash runup loses energy due to percolation, gravity and friction. The remaining swash moves laterally into the adjacent cusp embayments where less energy is lost due to the less permeable nature of the embayment sediment. Erosion occurs in the embayment and material is deposited offshore of the embayment forming a delta. The next incoming wave is retarded by the return flow of the swash through the embayment and the swash is concentrated onto the cusp horn. This circulation of swash sets up an adjacent circulation cell to replace water that is moved on and offshore. The circulation cells form sequentially in the alongshore direction (in one or both directions). Thus, cusps form sequentially along the beach

as observed at Buffalo Beach. Consequently, the formation and maintenance of beach cusps was found to be a result of both erosion and deposition as part of the re-working and sorting process.

Sediment textual characteristics were determined using the Rapid Sediment Analyser (R.S.A) to assess differences in sorting, skewness and mean grain size between cusp horn and embayment samples and between beach samples. Invariably, it was found that the cusp horn consists of better sorted, coarser sediment than the cusp embayments. The degree of sorting was found to be associated with wave energy, where sorting increased with increasing wave energy as a result of increased re-working of the sediment in the nearshore and swash zone.

Statistical analysis (principle components analysis and Pearson Product-Moment correlation analysis) showed associations between beach cusp spacing and development and nearshore processes and parameters. The greatest association was found to be with the mean subaerial beach slope. Beach cusps formed more consistently on the higher sloped beaches and the cusps were more regular in their spacing. It was found that as the mean subaerial beach slope increased, so did the spacing of the cusps. There is a significant correlation between wave energy, slope and cusp morphology. Where energy is higher, the mean subaerial beach slope is steeper, the cusps are better developed (in terms of the vertical difference in height between the cusp horn and embayment) and they are spaced further apart. A significant correlation was found between the spacing of cusps and the distance of swash excursion, cusp spacing increasing with increasing swash excursion. Analysis indicated that the steeper the beach, the narrower the surf zone and the more surging the breaking waves. The swash excursion was longer for the steeper beaches where waves broke on the beach face. Where the surf zone was wider and the waves broke further offshore, the swash excursion was less and cusps were more closely spaced.

Utilising edge wave theory, it was found that edge waves could theoretically exist on all of the beaches investigated in terms of the wave climate and mean subaerial beach slope. Subharmonic edge waves were found, theoretically, to be the easiest and most likely to be excited in terms of the beach slopes and surf zone widths.

Using edge wave theory, and assuming a subharmonic mode 0 edge wave, a significant correlation was found between the measured cusp spacing at each beach and the predicted

cusps spacing. The use of edge wave theory adequately predicted the spacing of cusps on the beaches investigated illustrating a statistically significant result (a correlation coefficient of 0.774).

There appeared to be some limits of wave energy between which cusps were more likely to form. The observations of this study indicated that cusps did not form when there was little swell. Where wave heights were too large for the dimensions of the cusps and breaking waves overtopped the cusp horns, the cusped topography was destroyed. Assuming that the cusps were formed by the initial perturbation of edge waves, these minimum and maximum energy levels were determined as the limits for subharmonic excitation. These values varied between beaches and are a function of beach slope and wave period. Sufficient energy is needed to be reflected from the beach face for a standing wave (which interacts with the edge wave resulting in a longshore variation in wave height) to form. Similarly, if the wave is too large, the wave plunges instead of surging, energy is dissipated and insufficient energy is reflected to form a standing wave.

The Wright and Short model was used to classify the beaches in terms of their morphology. Observational data from the beaches, the surf scaling parameter and the Dean's parameter calculated for each beach indicated that the beaches investigated could be categorised toward the reflective end of the beach classification spectrum. This indicated that sufficient energy was reflected from the beach face for the existence of subharmonic edge waves.

The existence of a shoreward migrating bar further supported the observations that cusps formed during the transition from high energy (dissipative) to low energy (reflective) in terms of the Wright and Short model. The bar was representative of the transition from intermediate beach states (a ridge and runnel system) to a reflective beach state (characterised by beach cusps). The Dean's parameter indicated that, if the prevailing conditions continued, the bar may have moved up onto the beach face and formed a series of beach cusps as the beach became more reflective.

Spectral analysis of nearshore current data from a cusped and non-cusped beach illustrated oscillation associated with infragravity waves. The data indicated spectra typical of intermediate tending toward reflective beach states (in terms of the Wright and

Short model) with most energy at incident wave frequencies with some less significant energy at infragravity frequencies.

Significant wave groupiness was evident in the incident and infragravity frequency time series of the longshore, onshore-offshore velocity components and the depth components of the spectrum from the nearshore zone at both beaches. Wave groupiness (or 'surf-beat') is thought to be a predominantly edge wave phenomena (Bowen and Guza, 1978). This adds further support to the theoretical assumption that edge waves may exist on the beaches investigated.

Wave refraction analysis indicated that an longshore variation in wave energy may influence the spatial distribution of beach cusps along a beach. Wave refraction results indicated that cusps form preferentially where the energy is higher and it was observed that cusp development decreased in the direction of decreasing wave energy.

Time series data indicated that cusps form during the transition from high energy to low energy. Observations indicate that cusps are more likely to form when there is significant swell from the easterly quarter. Because of the sheltered nature of the eastern Coromandel Peninsula from the prevailing westerly weather pattern, cusps form when episodic easterly events provide sufficient energy to initiate cusp formation and this was indicated by wave refraction analysis.

To the best of the authors knowledge, this is the first investigation that has incorporated field observations, statistical analysis, edge wave theory, spectral analysis of current meter and wave refraction analysis to describe the initiation, formation and maintenance of beach cusps. The observations of this studied concurred with aspects of a number of recent studies of beach cusps. More recent investigations associate the development of cusps with edge waves and the results of this study add further support to this theory. The results are not conclusive but theoretical assessment and the spectral analysis results indicated that edge waves may be related to cusp initiation and spacing. With respect to this a simple theory of cusp formation, development and maintenance is proposed.

## 8.2 An hypothesis of cusp initiation, formation and development

From the above summary of the findings of this investigation, a tentative hypothesis of cusp formation and maintenance can be suggested.

Necessary are onshore, long period swell conditions where the wave approach is normal to the shore. Wave groupiness is a prerequisite to cusp formation on the eastern Coromandel where two wave trains of slightly different periods result in oscillation at 'surf-beat' frequencies.

Secondary edge waves develop at these lower infragravity frequencies as a result of this wave groupiness. The dynamics of the edge waves (the amplitude and wavelength) are determined by the external wave groupiness and the gradient and width of the surf zone over which they operate. A subharmonic edge wave develops where  $n=0$  because of the steep, reflective nature of the nearshore zone. The edge waves are trapped in the nearshore by refraction, diffraction and reflection from headlands.

The beaches on which the long period swell impinges are near reflective (according to the classification of Wright and Short), characterised by a steep beach face, a narrow surf zone and surging breakers. Little energy is lost by energy dissipation and significant wave energy is reflected from the steep beach. The reflected wave interacts with the incident and edge waves to form a standing wave.

The interaction of the edge wave, incident and reflected wave results in a longshore periodic variation in the wave height, and subsequently, set up. The edge wave extracts energy from the incident waves so substantial incident wave energy is initially needed for the growth of edge waves significant enough to re-work sediment in the nearshore. Edge waves create the initial perturbation which sets up cell circulation in the swash.

A range of sediment sizes is needed on the beach. The beach cusps develop due to the influence on the swash of the regular longshore variation in wave height (as a result of edge wave perturbation). This results in selective re-working of the sediment. The superposition of the incident and edge wave results in higher swash excursion at the edge wave anti-nodes resulting in erosion (forming the cusp embayment) and no motion at the edge wave nodes

(forming the cusp horns). This results in a cusped topography where the wavelength of the cusps is half the edge wave wavelength. Circulation of swash initiated by edge wave perturbation maintains the cusp form. The swash excursion distance determines the spacing of the cusps.

The spatial distribution of the cusps depends on the spatial distribution of wave energy along the beach. Cusp formation is initiated where wave energy and the beach slope are within the range for subharmonic excitation. If wave energy decreases along the length of the beach, as a result of refraction and diffraction, there may be insufficient energy to maintain the swash circulation initially set up by the edge wave perturbation and cusp development (in terms of relief) will decrease in the direction of decreasing wave energy. The spatial distribution can also be explained by curving shorelines providing end effects that may limit the spatial extent of edge wave excitation which may, in turn, limit the spatial distribution of cusps.

The dimensions of the beach cusps are a function of the edge wave wavelength which, in turn, is a function of the beach slope and the width of the surf zone. Consequently, the steeper the beach, the further apart the cusp horns will be spaced as the wavelength of the edge wave is longer in comparison to less steep beaches. The dimensions of cusps are also a function of wave energy, higher waves will cause cusps to be located higher on the beach face and will also result in better developed cusps (in terms of the vertical difference between the cusp horn and cusp embayment).

The interaction of edge waves, incident waves, reflected incident waves, the width of the surf zone, the breaking wave height and type, the slope of the beach face and sediment characteristics develop a cusped morphology that will maintain its form until destroyed by high energy conditions with waves that are too large and dissipative to maintain the cusp topography.

### **8.3 Inconsistencies**

There appears to be significant correlation between cusp morphology and the theory of edge waves, the data from this study adding further support to the theory well documented in the

literature that edge waves provide the initial template for cusp spacing. However, there are several inconsistencies with the theory that have been noted during the course of this study.

Principle components analysis indicated a lack of correlation between wave period and cusp spacing. This lack of correlation disputes edge waves as a causative mechanism as the predictive equation for the spacing of cusps utilising edge wave theory uses the edge wave period (which for a subharmonic edge wave is twice that of the incident wave period). This lack of correlation may be explained by the fact that observations of cusps and visual estimations of the wave period were undertaken after cusp formation and may not represent the wave period at the time of cusp formation.

The minimum wave height for subharmonic excitation is low for all the beaches investigated (0.01-0.4 m) indicating the subharmonic edge waves and beach cusps could develop under very low energy conditions whereas observations indicate that cusps don't form in minimal swell conditions. This may be explained in terms of sufficient energy being needed for energy to be transferred from the incident wave to the edge wave for the edge wave motion to be sufficient to influence the beach topography. Even though edge wave motion may be present at a beach, there may be insufficient wave energy for the formation of cusps.

The spectral analysis of Buffalo and Rings Beach illustrated significant wave groupiness that may be indicative of edge wave motion in the nearshore zone at both beaches. If edge waves are thought to be responsible for the initiation of cusps then it could be assumed that cusps should have developed on Buffalo Beach but the beach remained planar. This may have been explained by a lack of wave energy but wave heights were similar to other occasions when cusps were observed to form on Buffalo Beach.

The mean subaerial beach slope and the wave period are variable on a beach and a number of beach slopes and wave periods could be assumed to represent the conditions on the beach and used in the predictive model (Eq. 4.9), providing a misleading correlation (or lack thereof).

The edge wave model for the prediction of cusp spacing involves the use of modes that describe the offshore behaviour of the edge wave. A number of modes can be viable for any one beach and the ability to use a number of different modes means that results and correlations are altered by the choice of mode.

#### **8.4 Areas where further research is needed.**

Several areas of this study can be expanded on to produce a larger database that may more conclusively indicate the mechanisms of cusp formation and maintenance.

Nearshore current data needs to be collected concurrently with time series data. Thus, possible edge wave motion can be directly related to changes over time in cusp morphology.

The spectral analysis of the current data needs to include coherence and phase analysis to assess if the long period motion is standing or progressive in the longshore direction.

Using an array of current meters would be beneficial to assess longshore and offshore changes in long period wave motion to investigate the extent and spatial influence of edge wave motion.

Data of non-cusped beaches needs to be included in any investigation so the differences between cusped and non-cusped beaches can be investigated. The comparison would better indicate those parameters and processes associated with the initiation, formation and maintenance of a cusped beach.

## *Appendix A*

### *Sediment analysis and classification*

The R.S.A (Rapid Sediment Analyser) was used to investigate the textual characteristics of cusp horn and embayment sediment samples from each observation period.

The R.S.A consists of 2.0 m tube full of fresh water. A cassette for the release of sediment is placed at the top of the fall tube. At the bottom of the fall tube is a collecting pan connected to an electronic balance by cables. The electronic balance (accurate to  $\pm 0.01\text{g}$ ) is placed on top of the settling tube. The balance records the submerged weight of each fraction of accumulated sediment from the suspended collecting pan at a predetermined time interval.

Signals from the balance are converted to data of the cumulative submerged mass of the accumulated sediment on the collecting pan which are processed using the Apple Mac system and printed. A program written by Dr. W P De Lange, Earth Science Dept., University of Waikato, performs a statistical analysis of the particle size data.

Samples were washed through a 1.75 phi sieve to remove the gravel and a 4.00 phi sieve to extract the silt and clay fraction. Sediment (approximately 50.0 g) was placed in the cassette and it's release initiates the computer which collects the data and produces a hard copy.

The textual parameters - mean grain size, skewness and sorting, calculated by the program, were used in the analysis.

## *Appendix B*

### *Sediment classification*

Table B.1 The phi scale and corresponding mm size classes and the verbal Wentworth (1922) size classes for the sand to pebble size range (Source: Healy and Dell, 1982).

Phi	Millimeters (mm)	Wentworth Size class
-6.0 - -2.0	64.00 - 4.00	pebble
-2.0 - -1.0	4.00 - 2.00	granule
-1.0 - 0.0	2.00 - 1.00	very coarse sand
0.0 - 1.0	1.00 - 0.50	coarse sand
1.0 - 2.0	0.50 - 0.25	medium sand
2.0 - 3.0	0.25 - 0.125	fine sand
3.0 - 4.0	0.125 - 0.0625	very fine sand

Table B.2 Sorting values for graphically obtained statistics as devised by Folk and Ward (1957) (Source: Lewis, 1984).

Sorting (phi)	Verbal description
0 - 0.35	very well sorted
0.35 - 0.50	well sorted
0.50 - 0.71	moderately well sorted
0.71 - 1.00	moderately sorted
1.00 - 2.00	poorly sorted
2.00 - 4.00	very poorly sorted
4.00 +	extremely poorly sorted

## *Appendix B (cont.)*

Table. B.3 Skewness values for graphically obtained statistics as devised by Folk and Ward (1957)

(source: Lewis, 1984).

Skewness	Verbal description
+1.00 - +0.30	strongly fine skewed
+0.30 - +0.10	fine skewed
+0.10 - -0.10	near symmetrical
-0.10 - -0.30	coarse skewed
-0.30 - -1.00	strongly coarse skewed

## *Appendix C*

### *Sample catalogue*

Table C.1 Catalogue of samples used in the textual analysis

Beach	Position on Profile	Sample Number	Sample Remaining
Buffalo 3/91	Horn	W 93127	✓
	Embayment	W 93128	✓
Buffalo 4/91	Horn	W 93129	
	Embayment	W 93130	
Buffalo 7/92	Horn	W 93131	
	Embayment	W 93132	✓
Cooks 5/92	Horn	W 93133	✓
	Embayment	W 93134	✓
Hahei 5/92	Horn	W 93135	✓
	Embayment	W 93136	✓
Hahei 8/92	Horn	W 93137	
	Embayment	W 93138	

## *Appendix C (cont.)*

### *sample catalogue*

Table C.1 continued.

Kuaotunu 3/91	Horn	W 93139	✓
	Embayment	W 93140	✓
Maramaratotara 3/92	Horn	W 93141	✓
	Embayment	W 93142	✓
Maramaratotara 5/92	Horn	W 93143	✓
	Embayment	W 93144	✓
Maramaratotara 7/92	Horn	W 93145	✓
	Embayment	W 93146	✓
Maramaratotara 8/92	Horn	W 93147	
	Embayment	W 93148	
Rings 3/91	Horn	W 93149	✓
	Embayment	W 93150	✓
Rings 3/92	Horn	W 93151	✓
	Embayment	W 93152	✓
Rings 5/92	Horn	W 93153	✓
	Embayment	W 93154	✓
Rings 8/92	Horn	W 93155	
	Embayment	W 93156	
Wharekaho 5/92	Horn	W 9315	✓
	Embayment	W 93158	✓
Wharekaho 7/92	Horn	W 93159	
	Embayment	W 93160	

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