ELSEVIER

Marine Geology 186 (2002) 211–228

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

A field based classification scheme for gravel beaches

Richard Jennings [a,*], James Shulmeister [b]

[a] School of Earth Sciences, Victoria University of Wellington, P.O. Box 600, Wellington, New Zealand
[b] Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

Received 6 August 2001; received in revised form 5 February 2002; accepted 17 April 2002

Abstract

A tripartite classification of gravel beaches, based upon morphodynamic properties, is proposed and demonstrated for 42 New Zealand beaches. The main advantage of this scheme is that it is based on simple visual classification that can be applied globally in the field and is underpinned by morphodynamic differences between the beach types. The three types identified from the results are: (1) pure gravel beach; (2) mixed sand and gravel beach; (3) composite gravel beach. Pure gravel beaches have steep slopes (tan $\beta = 0.08$–0.24) and gravels extending from the storm berm to below mean low water spring tide level. Mixed sand and gravel beaches have moderate slopes (tan $\beta = 0.04$–0.13) with sand and gravel entirely mixed both cross-shore and at depth. Composite gravel beaches have a steep gravel berm fronted by a low-angle intertidal terrace, with overall beach slopes of tan $\beta = 0.05$–0.14. On composite beaches there is distinct hydrodynamic cross-shore sorting of the sand and gravel component. These broad types are tested using discriminant analysis and the three classes are shown to be highly significant ($F = 16.24$, df = 8, $P < 0.00005$). The key discriminating variables are Iribarren number, beach width, average grain size and storm berm height.

Keywords: beach; classification; gravel; morphodynamics; New Zealand

1. Introduction

The last two decades have seen an increase in research on gravel beaches from a wide variety of coastlines. This research has covered all temporal and spatial scales, from tidal changes in beachface processes and morphology (Mason et al., 1997; Stapleton et al., 1999), through sub-decadal response of barriers to sea level rise (Orford et al., 1995), to Holocene evolution of the coastline (Long and Hughes, 1995; Soons et al., 1997). This gravel beach literature can be broken down into two main areas of research: (1) gravel barrier evolution (e.g. Carter and Orford, 1988; Forbes et al., 1991; Forbes et al., 1995; Orford et al., 1996; Jennings et al., 1998); and (2) gravel beach processes, morphology and sediments (e.g. Bluck, 1967; Kirk, 1975; Orford, 1977; Powell, 1988, 1990; Nicholls and Wright, 1991; Sherman, 1991; Sherman et al., 1993; Mason et al., 1997). Despite this increased focus on gravel beaches there are some surprising deficiencies, including the absence of a widely applicable process-based

* Corresponding author.
E-mail address: gravelbeach@hotmail.com (R. Jennings).

0025-3227/02/$ – see front matter
PII: S0025-3227(02)00314-6

classification scheme. This paper addresses this issue.

The morphodynamic approach has been a central component of sandy beach research since its formal introduction by Wright and Thom (1977). One of the major outcomes of this approach has been the development of physically based beach classification models (e.g. Chappell and Eliot, 1979; Short, 1979; Wright and Short, 1984; Masselink and Short, 1993; Brander, 1999; Ranasinghe et al., 1999). Gravel beaches predominantly fall within the reflective domain of the Short (1979) model (Carter and Orford, 1984; Short, 1999, fig. 9.5). However, gravel beaches cover a very wide range of morphological forms and they can have a wide variety of sedimentological assemblages and occur in many different environmental settings (Table 1). Consequently, it is unclear whether gravel beaches can be adequately classified as reflective, especially considering the low amount of wave reflection, 10%, measured by Powell (1990) on a gravel beach.

There have been attempts at classifying gravel beaches by their sedimentary assemblages or morphology, although no scheme is applicable to all the different gravel beaches observed. One of the first classification schemes was based upon cross-shore sediment sorting and clast analysis of particle shape (Bluck, 1967). Bluck identified two distinct beachface sedimentary facies assemblages, the Sker and Newton beach types, representing high-wave and low-wave energy, respectively. Both of these beach types are composed of gravel with a size range of -4 to -7ϕ and fronted by an intertidal rock platform. Orford (1975) tested the Bluck model and showed that both the low- and high-energy sedimentary assemblages could occur on one beach through time. The beach in Orford's study had a D_{50} of $\sim -5\phi$, and the gravel berm extends seawards onto an intertidal sand platform. Williams and Caldwell (1988) also tested the classification scheme of Bluck (1967), and found that on higher-energy gravel beaches better discrimination in sediment sorting could be made using particle size rather than shape. Utilizing a beachface transition model developed for sandy beaches, Caldwell and Williams (1985) attempted to classify gravel beaches by the trigonometric shape of their profiles and berm locations. They showed that there was a statistically significant difference between the 10 different profile configurations identified, but they were unable to determine the primary physical processes which control profile evolution. The complexity inherent with this statistical approach has hindered its wider application. Carter and Orford (1993) suggested that there are two key types of gravel beach which are based upon morphology; (1) a single slope from the beach crest to wave base, ignoring small scale bars and berms, and (2) a composite slope from beach crest to wave base, with a steep upper intertidal zone and a low-angle lower intertidal zone.

Other than Bluck (1967), Caldwell and Williams (1985) and Carter and Orford (1993), gravel beach classifications have been developed with long-term barrier evolution as the main focus. This has resulted in strong regional bias with morphological descriptions of gravel beaches being derived from sediment starved or sediment limited systems, such as those in Canada (e.g. Carter et al., 1990; Orford et al., 1996) and the UK (e.g. Carter and Orford, 1988). This has less relevance for coastlines where sediment supply is virtually unlimited, such as the east coast of South Island, New Zealand (e.g. Shulmeister and Kirk, 1993, 1997). There has been no attempt to systematically contrast the major gravel beach types described in the literature and determine whether they represent different morphodynamic systems. One of the major problems is that the terminologies used to describe gravel beaches are not applied consistently. For example, there are few studies on gravel beaches where the entire beach profile from maximum wave runup to wave base is fully described and grain size data is often absent, with various terms such as shingle or coarse clastic being used.

To address the issue of gravel beach classification, a field study has been undertaken in New Zealand. The aim of this study is to identify different types of gravel beaches and test for systematic variations among them. The primary morphodynamic characteristics will be highlighted and their applicability to published data sets will be tested.

Table 1
Examples of gravel beach morphology from the literature are shown using the descriptions provided by the authors of each paper

Reference	Grain size	Slope	Wave regime	Tide	Scale of study
Nicholls and Webber, 1987	shingle	0.16–0.2	N/A	mesotidal	Quaternary
Carr, 1971	pebble or larger	∼0.16	maximum 12 m	N/A	event
Bradbury and Powell, 1992	D_{50} 16 mm	0.08–0.1	1/100 yr storm 1.8–3.5 m	mesotidal	event
Powell et al., 1992	D_{50} approx. 54 mm	1:7	Hsig approx. 1.7 m	N/A	event
Sanders, 2000	fine sand to coarse gravel	15–50°	low energy	microtidal	event
Sherman, 1991	1- 5–200 mm 2- 4–64 mm	1- 11° 2- sand: 1–2°; gravel: 5–7°	1- collapsing/surging 2- spilling–plunging	mesotidal	event
Bluck, 1967	gravel berm: 16–95 mm	N/A	N/A	N/A	event
Orford, 1975, 1977	D_{50} 52 mm	N/A	90% <4 m	meso/macro	event
Caldwell and Williams, 1985, 1988	-2 to -8ϕ	approx. 0.1–0.25	N/A	macrotidal	event
Mason and Hansom, 1989	upper: 2.6 mm lower: 0.36 mm	upper 4–7° lower 0–2°	0.5 to >2 m	N/A	event
McKay and Terich, 1992	4 to -8ϕ	0.1–0.14	mean annual Hsig 2.8 m	meso/macro	event
Sherman et al., 1993	4–64 mm	sand: $1–2^0$ gravel: 5–7°	spilling–plunging	mesotidal	event
Mason et al., 1997	N/A	1.2–5.7°	Hsig = 0.15–0.19 m	macro	tidal
Stapleton et al., 1999	D_{50} 11 mm	approx. 0.07	N/A	N/A	tidal
Shulmeister and Kirk, 1993	N/A	N/A	medium/high energy (95% of swell <2.4 m)	microtidal	Holocene
Soons et al., 1997	N/A	N/A	av = 1.3 m, max = 6.3 m	microtidal	Holocene
Kirk, 1975, 1980	0.25–16 mm	$5–12^0$	east coast swell	micro/meso	all

Due to the use of varied terminology and scales of measurement, it is difficult to compare between beaches.

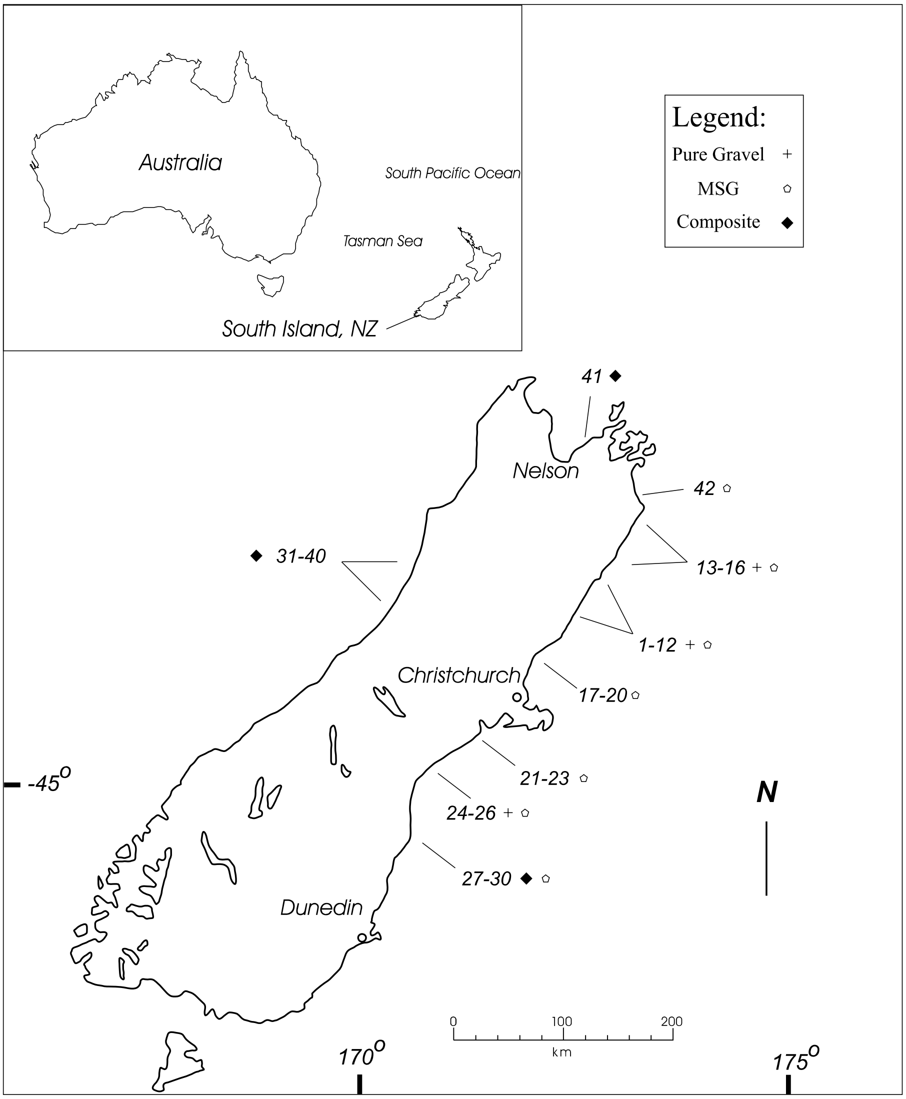

Fig. 1. Location of field sites, South Island New Zealand. Refer to text and Table 2 for physical properties of each beach. Numbers relate to beach location number in Table 2 and the symbols represent those beach types in each area.

2. Methods

Forty two gravel beaches were studied from around the coastline of South Island, New Zealand (Fig. 1). At each site, beach width, storm berm height, number of berms, beach slope, and grain size were measured. The local wave climate was determined using data from Pickrill and Mitchell (1979) and the tidal range was calculated from the New Zealand Nautical Almanac (NZNA, 2000).

Every beach survey was undertaken at low tide using either electronic or manual levels. The maximum seaward extent of the survey was controlled by wave conditions on the day. For example, a survey on a beach with a breaking wave height of >1 m prevented the survey from reaching the beach step, if one was present. A single cross-shore transect was taken at each site, the location of the transect was determined by the presence or absence of cusps. On all of the beaches studied there were zones of well-developed cusps and areas of no cusp formation, there was no spatial pattern to their presence or absence. All of the transects were taken in the area of beach with no cusp development to ensure continuity between surveys. On the gravel beaches with a large surf zone only that part of the beach exposed at low tide was surveyed.

Three sediment samples were taken at each beach: (1) on top of the highest (storm) berm; (2) at the high-tide mark; and, (3) in the swash zone. For the high tide and storm berm samples the *B*-axis of 50 randomly selected clasts were measured in the field. Swash zone sediment samples of equal volume were taken from the top 10 cm of the bed and dry sieved in the laboratory, using half-ϕ intervals. Grain size has been compared using the Wentworth Scale (Krumbein, 1941).

Two beach slope measurements were calculated for all beaches. The first measurement was the beachface slope, taken from the top of the highest berm to low tide or, the most seaward point surveyed (Fig. 2). This slope value is the average value for the beach and is thus used in the calculation of the Iribarren number. It is also combined with the average grain size data to study the grain size–slope relationship. The second slope measurement was the active profile slope, which is defined as the distance between high- and low-tide levels on the day of survey (Bascom, 1951). The active profile slope value is directly comparable to the swash zone sediment sample and can also be used to evaluate the grain size–slope relationship on beaches. Both of these grain size–slope measurements are calculated because they are the two main techniques used in the literature.

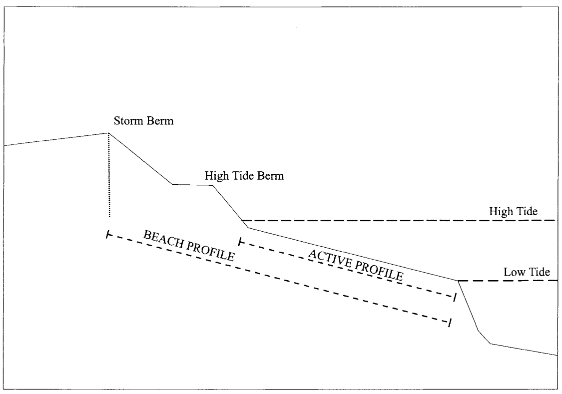

Fig. 2. Schematic representation of slope calculations. The active profile is taken from the point of low tide to the point of high tide on the day of survey (after Bascom, 1951). The beachface profile is calculated for the entire beachface, from low tide to the highest (storm) berm.

Combining the beachface slope values for each site and the wave data from Pickrill and Mitchell (1979), the Iribarren Number (Battjes, 1974) was calculated for each beach, using

$$\xi = \frac{tan\ \beta}{(H_o/L_o)} \quad (1)$$

where tan β is the beachface slope, H_o is offshore wave height (m), L_o is offshore wave length (m). The Iribarren number was calculated because it is based upon beach slope and avoids the prior selection of a sediment parameter (Anthony, 1998). Also, the Iribarren number has been shown to be a good morphodynamic discriminator between end members on the dissipative–reflective scale (Bauer and Greenwood, 1988).

The differences between beaches based upon the measured variables was established using linear discriminant analysis. Discriminant analysis defines a combination of these variables which best differentiate among groups, termed the canonical coefficient. The maximum number of linear canonical coefficients will be equal to the number of groups minus 1, and these are independent of each other (Engelman, 1998; StatSoft, 2001). The program SYSTAT (Version 9.01) was used for this analysis. The statistical significance of the discriminant analysis is tested using the Wilks' Lambda multivariate analysis of variance statistic (Engelman, 1998). SYSTAT transforms the Wilks' Lambda results into an F statistic which can be compared to standard F distribution tables. Discriminant analysis has been used previously to test a predictive model for classifying sandy beaches (Wright et al., 1985).

3. Results

A number of distinctly different gravel beach morphologies were found in the field and three

Fig. 3. An example of a pure gravel beach, Canterbury Bight, New Zealand. Gravel dominates from the top of the storm berm to below the low-tide mark.

fundamental forms recur. The first type is a pure gravel beach and the other two types are mixed sediment beaches. The pure gravel type has a linear slope with minor berms and strong sediment sorting (Fig. 3), similar to the simple linear slope type described by Carter and Orford (1993). The first mixed type is the mixed sand and gravel (MSG) beach, it is composed of entirely intermixed sand and gravel throughout its profile (Fig. 4). The second mixed type is distinctly different because the sand and gravel components are separated in the cross-shore direction (Fig. 5).

Fig. 4. A MSG beach, Orongorongo, Wellington, New Zealand. The MSG shows good surficial sediment sorting, however this does not extend below the top sediment layer.

Fig. 5. Composite gravel beach, Cable Bay, Nelson, New Zealand. The cross-shore sorting of the composite beach is one of its main features.

This type is similar to the composite beach described by Carter and Orford (1993) and the term is retained. The pure gravel and MSG beaches are all located on the east coast of South Island, whilst the composite beaches are predominantly located on the west coast of South Island, with one on the east and another on the north coast (Fig. 1).

The steepest beachface slopes were observed on the pure gravel beaches, with values between tan $\beta = 0.08$ and 0.25, and an average beachface slope of tan $\beta = 0.18$ (Table 2, Fig. 6). Composite beaches, with beachface slope values of tan $\beta = 0.05$–0.14 and an average of tan $\beta = 0.1$, were only slightly steeper than MSG beaches with tan $\beta = 0.04$–0.13, and an average of tan $\beta = 0.08$ (Table 2, Fig. 6). The active profile slope results are slightly different, the pure gravel beaches have slopes of tan $\beta = 0.09$–0.19 and an average active profile slope of tan $\beta = 0.12$. The composite beaches have active profile slopes of tan $\beta = 0.03$–0.11 and an average slope of tan $\beta = 0.06$, which is significantly different to the beachface slope results. The MSG beaches have active profile slopes in the range of tan $\beta = 0.05$–0.14, and an average slope of tan $\beta = 0.08$, which is the same as the beachface slope result.

Composite gravel beaches had the narrowest range of average mean grain sizes, with D_{50} values from -4.17 to -5.64ϕ and an average D_{50} of -4.99ϕ, whilst MSG beaches were finer, with a larger D_{50} range from -1.65 to -5.21ϕ and an average D_{50} of -3.93ϕ. Pure gravel beaches encompassed the coarsest mean grain sizes, with a D_{50} range of -2.39ϕ to -6.13ϕ, but they had a lower mean D_{50} than composite beaches with a value of -4.21ϕ. Looking at the active profile zone separately, the sediment size patterns are different. The composite gravel beaches have the largest sediment size range which includes the finest sediments, with D_{50} values of 3.09 to -3.7ϕ and a mean D_{50} of -2.74ϕ. MSG beaches also have finer D_{50} values than the average, between 0.42 and -3.4ϕ and the smallest mean D_{50} -1.42ϕ. The grain size range for the pure gravel beaches is -1.82 to -5.08ϕ with a mean D_{50} of -3.53ϕ.

On the pure gravel beaches there is a distinct size grading from the swash zone to the storm berm, with the largest sediment being found on the storm berm (Table 2). This pattern is repeated on the composite beaches (Table 2) and it is more visually apparent due to the sand component in the lower intertidal (Fig. 5). On MSG beaches,

Table 2
Morphological parameters of beaches in this study

Type	Beach site	Tide	Beach slope	Average grain size (ϕ)	Storm berm grain size (ϕ)	High-tide grain size (ϕ)	Swash Grain Size (ϕ)	Hsig (offshore m)	Average wave period (s)	Iribarren No.	Beach width (m)
PG	9	micro	0.14	−2.39	−2.26	−2.90	−1.82	1.25	9.00	2.27	51.63
PG	10	micro	0.13	−2.49	−2.57	−2.79	−2.01	1.25	9.00	2.12	50.40
PG	15	micro	0.23	−6.13	−6.59	−6.48	−4.63	1.25	9.00	3.79	23.89
PG	16	micro	0.23	−6.03	−6.54	−6.35	−4.39	1.25	9.00	3.79	25.04
PG	25	micro	0.10	−2.99	−3.66	−2.01	−2.82	1.25	9.00	1.58	38.40
PG	11	micro	0.24	−5.21	−5.58	−4.88	−5.08	1.25	9.00	4.00	18.50
PG	12	micro	0.20	−4.20	−2.66	−5.04	−3.99	1.25	9.00	3.26	28.01
MSG	1	micro	0.11	−3.85	−5.22	−1.65	−1.54	1.25	9.00	1.83	32.22
MSG	2	micro	0.11	−4.85	−5.14	−5.47	−2.77	1.25	9.00	1.82	43.41
MSG	13	micro	0.12	−4.41	−1.71	−5.89	−0.11	1.25	9.00	1.85	36.44
MSG	14	micro	0.12	−5.21	−5.83	−5.60	−2.39	1.25	9.00	1.94	31.96
MSG	28	micro	0.08	−4.89	−5.14	−5.47	−3.27	1.25	9.00	1.35	55.94
MSG	3	micro	0.09	−2.88	−4.31	−0.04	−0.33	1.25	9.00	1.48	46.55
MSG	4	micro	0.09	−4.72	−5.36	−5.14	−1.38	1.25	9.00	1.43	48.98
MSG	5	micro	0.08	−3.73	−4.28	−4.29	0.08	1.25	9.00	1.23	63.74
MSG	6	micro	0.08	−3.93	−3.04	−5.18	−0.48	1.25	9.00	1.31	61.15
MSG	7	micro	0.09	−1.65	0.92	−1.10	−2.75	1.25	9.00	1.37	65.75
MSG	8	micro	0.08	−1.75	0.94	−1.09	−2.90	1.25	9.00	1.25	69.66
MSG	17	micro	0.09	−4.84	−5.60	−5.06	−1.85	1.25	9.00	1.40	39.83
MSG	18	micro	0.09	−3.88	−4.81	−3.72	−1.62	1.25	9.00	1.43	50.85
MSG	19	micro	0.04	−3.74	−3.49	−4.82	0.36	1.25	9.00	0.68	68.00
MSG	20	micro	0.07	−3.38	−3.49	−4.21	−0.69	1.25	9.00	1.08	50.95
MSG	21	micro	0.09	−4.05	−4.83	−4.08	−2.15	1.25	9.00	1.41	76.10
MSG	22	micro	0.06	−3.18	−3.68	−3.51	−1.53	1.25	9.00	0.90	98.00
MSG	23	micro	0.07	−4.07	−4.64	−4.55	−1.12	1.25	9.00	1.08	60.00
MSG	24	micro	0.09	−4.25	−4.49	−4.59	−3.40	1.25	9.00	1.39	48.00
MSG	26	micro	0.06	−3.82	1.24	−5.30	−1.35	1.25	9.00	0.97	76.80
MSG	27	micro	0.08	−4.44	−5.10	−4.75	−2.02	1.25	9.00	1.35	49.35
MSG	30	micro	0.08	−4.10	−5.26	−3.63	0.42	1.25	9.00	1.31	32.00
MSG	31	meso	0.08	−4.85	−5.99	−4.44	−0.14	1.25	9.00	1.26	74.00
MSG	42	micro	0.08	−3.74	−4.66	−3.66	−1.09	1.25	9.00	1.32	34.00
COMP	29	micro	0.10	−4.83	−5.63	−5.09	−0.92	1.25	9.00	1.55	11.48
COMP	32	meso	0.07	−5.34	−5.89	−5.79	−2.67	2.00	7.00	0.69	63.20
COMP	33	meso	0.07	−4.56	−4.33	−5.53	−2.09	2.00	7.00	0.69	51.08
COMP	34	meso	0.05	−4.77	−5.53	−4.85	−2.78	2.00	7.00	0.53	63.26
COMP	35	meso	0.13	−5.09	−5.68	−5.25	−3.71	2.00	7.00	1.23	34.00

Table 2 (*Continued*).

Type	Beach site	Tide	Beach slope	Average grain size (φ)	Storm berm grain size (φ)	High-tide grain size (φ)	Swash Grain Size (φ)	Hsig (offshore m)	Average wave period (s)	Iribarren No.	Beach width (m)
COMP	36	meso	0.07	−5.15	−5.76	−4.77	−4.65	2.00	7.00	0.64	42.00
COMP	37	meso	0.12	−4.17	−4.85	−4.58	0.01	2.00	7.00	1.17	43.38
COMP	38	meso	0.14	−5.64	−6.46	−5.28	−4.55	2.00	7.00	1.40	24.00
COMP	39	meso	0.08	−4.85	−5.07	−5.57	−2.49	2.00	7.00	0.76	66.00
COMP	40	meso	0.11	−4.80	−5.78	−4.75	−0.77	2.00	7.00	1.11	32.00
COMP	41	meso	0.15	−5.64	−5.91	−5.41	−5.55	1.00	6.00	1.85	42.72

The beach site column refers to their location shown in Fig. 2.

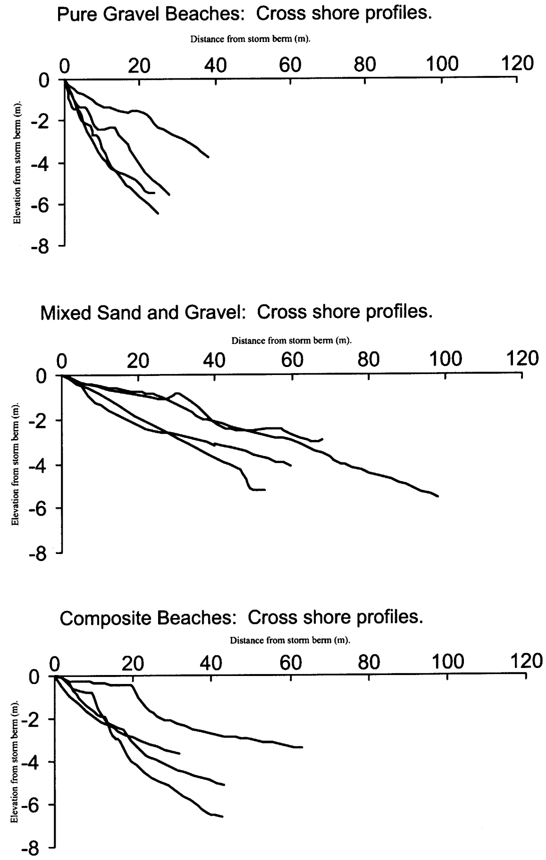

Fig. 6. Examples of cross-shore profiles for each of the beach types. Four profiles have been selected to show the widest range of profile shapes. All profiles are plotted on a common scale. The gravel beaches are the steepest, and the MSG beaches the widest.

although the swash zone sediment is on average coarser than the high tide or storm berm sediment, there is not a large difference between them (Table 2). In several cases, the storm berm sediment is finer grained.

The number of berms and storm berm elevation was variable within each of the three types, and no visual pattern among the types was apparent. Iribarren number values were quite different between pure gravel beaches and the two mixed beach types. Pure gravel beaches were predominantly based in the steep beachface and collapsing wave domain (Table 2). The other two types were both located in the moderate-steep beachface and plunging wave domain, although on average the composite gravel beaches had lower values, closer to the spilling wave domain than the MSG beaches (Table 2).

A comparison of the grain size and slope relationship for the active profile and swash zone sediment indicates that there is no relationship (Fig. 7A). When the average grain size from the entire beach is plotted against the beachface slope value only the pure gravel beaches fit a linear trend of increasing slope with increasing grain size (Fig. 7B). The grain size–slope relationship for the beachface values of the pure gravel beaches has been compared with average values from Shepard (1963, from Komar, 1998) (Fig. 8). The linear relationship for the pure gravel beaches has an r^2 value of 0.82, which shows that there is a strong positive correlation between grain size and slope at the beachface scale for pure gravel beaches.

For the discriminant analysis, beach width, storm berm height, number of berms, active pro-

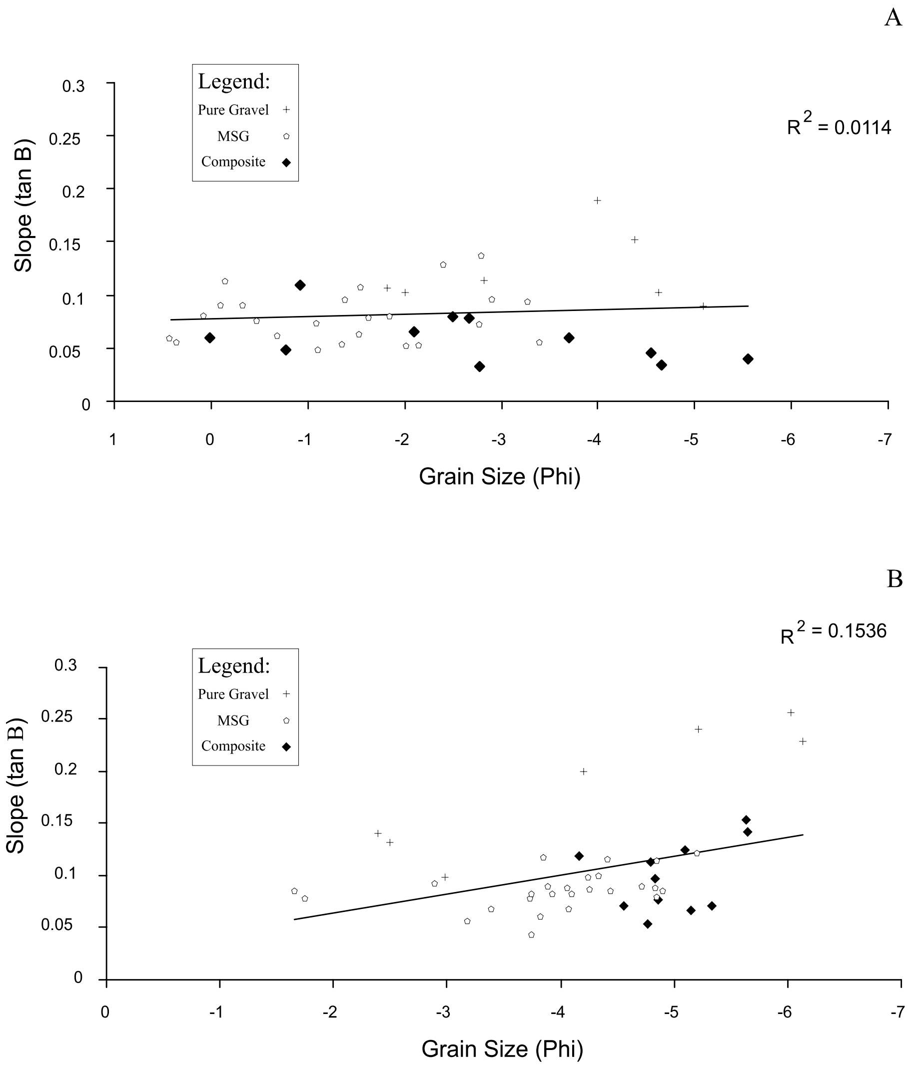

Fig. 7. (A) Swash grain size versus active profile slope for all beaches. Grain size is shown in ϕ values. The low r^2 value shows that there is no significant linear relationship. (B) Average grain size versus beachface slope for all beaches. The low r^2 value for the data shows that the linear relationship between grain size and slope for all the beaches combined is not significant.

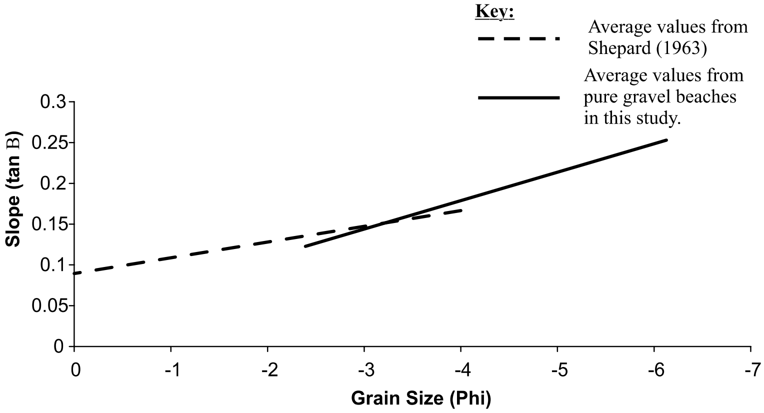

Fig. 8. A comparison of average grain size–slope values from Shepard (1963) and the pure gravel beaches in this study. The values from Shepard are taken from Komar (1998). The values for the pure gravel beaches are based upon seven field sites. There is a good fit between the lower values from the pure gravel beaches and the larger grain sizes from Shepard. The line of best fit for the pure gravel beaches has an r^2 value of 0.84. This relationship is significant, but was not present for the other beach types in this study.

file slope, Iribarren number and average grain size were used to establish the three beach type classification. The beachface slope was not included as it had been utilized in the calculation of the Iribarren number, and would therefore potentially bias the results. Similarly, the three grain size measurements from the active profile, high tide and storm berm, were not included as they were

Table 3
Statistical output from the discriminant analysis

Between groups *F*-matrix				
	Pure gravel	MSG	Composite gravel	
Pure gravel	0.000			
MSG	13.106	0.000		
Composite gravel	25.587	9.673	0.000	
Canonical discriminant functions – standardized by within variances				
	Function 1	Function 2		
Beach width	0.994	1.340		
Storm berm height	−0.543	−1.032		
Number of berms	−0.036	0.245		
Active profile slope	0.265	0.143		
Average grain size	0.857	0.388		
Iribarren number	1.680	0.318		
Jacknifed classification matrix				
	Pure gravel	MSG	Composite gravel	% correct
Pure gravel	6	1	0	86
MSG	2	22	0	92
Composite gravel	0	1	10	91
Total	8	26	10	90

The between groups *F*-matrix shows the similarity between beach types. Pure gravel and MSG beaches are most similar, whilst pure gravel and composite gravel have the greatest difference. The canonical discriminant functions show the usefulness of variables in the discrimination between beach type. The jacknifed classification matrix tests the linear discriminant function. It shows that the prediction for MSG beaches is 92%.

combined to calculate the average grain size. In the analysis the F statistic is used to test for equality among group means, with the groups being pre-defined as pure gravel, MSG and composite gravel. This statistic represents the closeness of the group centroids, which is related to the canonical scores plot. The between groups F-matrix in Table 3 indicates that pure gravel and MSG beaches are most similar, whilst pure gravel and composite gravel beaches have the greatest difference. The relative importance of each variable in the model is also tested using the F statistic. The most important variable is that with the greatest difference between group means. Table 3 shows that the Iribarren number, beach width, average grain size and storm berm height are the most important discriminators in that order.

The Jacknifed Classification Matrix was used to cross-validate the statistical separation of beaches into groups. It shows that the model correctly distinguishes 86% of the pure gravel beaches, 92% of the MSG beaches and 91% of the composite gravel beaches (Table 3). Overall, the model identifies 90% of the beaches correctly (Table 3). There are three groups in this analysis and, therefore, two canonical coefficients. The first canonical coefficient explains 90% of the variance between the groups, which indicates that it captures most of the variability among the beach types and that the beach types are significantly different from each other. The first and second canonical coefficients are plotted in Fig. 9, here termed factors 1 and 2, respectively. There is a clear discrimination among the three beach types based upon this analysis (Fig. 9). Results from the Wilks' Lambda test show that these results are significant ($F = 16.24$, df = 8, $P < 0.00005$).

4. Discussion

The outcome of the discriminant analysis confirms the visual results and the assumption that there are three basic types of gravel beach and it indicates that they are statistically different (Fig. 9). The location of the MSG and pure gravel beaches on the east coast of South Island and composite beaches on the west coast could suggest that there is a control upon beach type other than those presented here, such as sediment source. The deep-water wave regime is the same for the pure gravel and MSG beaches, yet they represent different morphologies and sediment architecture. This suggests that there is a relationship between sediment supply, wave regime and beach type. However, the occurrence of these beaches in other

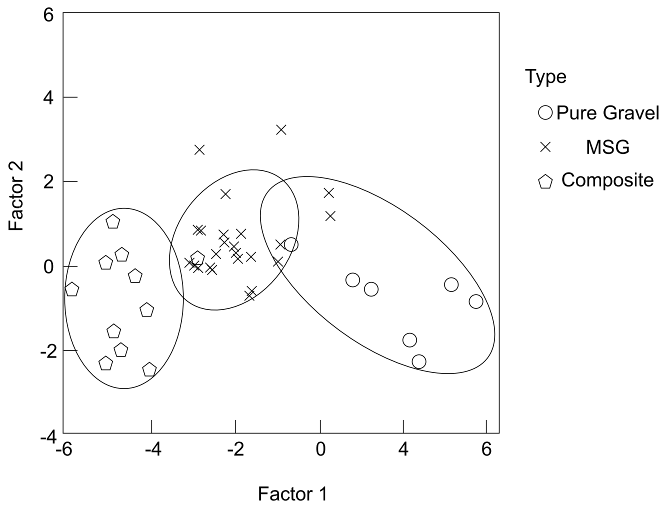

Fig. 9. Canonical scores plot, produced by discriminant analysis. Factor 1 represents the first canonical variable, which explains 89% of the variance. This variable is a function of beach slope, grain size and Iribarren value. The ellipses are a best fit to the linear relationship and it can be clearly seen that there is good discrimination between the three beach types.

areas of New Zealand and elsewhere in the world (e.g. Zenkovich, 1967; Sherman, 1991; Carter and Orford, 1993; Mason, 1997) suggests that they are not unique to this study and a universal classification scheme, which defines the morphology, sedimentary organization and process dynamics at the micro–meso scale (seconds to years) is appropriate.

The three beach types represent quite different morphologies, dependent upon Iribarren Number, beach width, average grain size and storm berm height. Therefore, if these beaches are distinct morphologically, it can be assumed that they will also have different process signatures (Wright and Short, 1984).

4.1. The morphodynamic model

Based upon these results a model is presented which develops a scheme for differentiating between gravel beach types, which describes their morphology, sediments and hydrodynamics. The following is a proposal for a three state model for gravel beaches. The three states are: (1) pure gravel beach; (2) MSG beach; (3) composite gravel beach. This model utilizes the concept of morphodynamics to couple the visual morphology with its formative hydrodynamic regime (Wright and Thom, 1977) and is initially intended for micro-meso tidal beaches only. The hydrodynamic regime proposed for the three beach types is based upon the current literature.

4.1.1. Type 1: pure gravel beach (Fig. 10A)

The pure gravel beach is dominated by gravel throughout its profile, with a mean grain size range from -2 to -6ϕ. It is highly reflective at all stages of the tidal cycle (Carter and Orford, 1993). Surf zone processes will be absent and edge wave development, with associated cuspate morphology, will control the morphodynamic regime (Sherman et al., 1993). Cusps can be either accretionary or erosional (Sunamura and Aoki, 2000). A steep beachface with slopes of $\tan\beta = 0.1$–0.25 can be maintained due to the high permeability of the gravel, which accentuates the asymmetry of swash (Quick and Dyksterhuis, 1994). Cross-shore sediment sorting is common and often well developed (Bluck, 1967). Beach widths are not large, ranging from 18 to 50 m. Surging and collapsing waves dominate under all but the most severe storms (Kemp, 1961), with an Iribarren number of 1.6–4.0. Under storm conditions a cycle of storm erosion and post storm recovery has been observed to occur on pure gravel beaches (Sherman, 1991). During storms the beachface is down-combed and flattened, and in the post-storm recovery phase lower shoreface bars develop and migrate up-slope (Sherman, 1991). On very coarse pure gravel beaches storm accretion has been observed, with build up of the most landward berm (Lorang et al., 1999).

4.1.2. Type 2: MSG beach (Fig. 10B)

The MSG beach is composed of fully MSG sediment both cross-shore (Kirk, 1980) and at depth (Fig. 11). Grain size will vary between coarse sand and pebble, 0.5 to -6ϕ. A single breakpoint dominates with little horizontal tidal translation, and it is associated with a well-formed and stable breakpoint step (Fig. 10B). Swash processes control the hydrodynamic regime, therefore, the swash zone will be the main area for sediment transport (Kirk, 1980). Little is known about the storm behavior of MSG beaches, although during storms the single breakpoint remains with little or no surf zone development (Kirk, 1980). Cuspate morphology may be highly developed with up to three vertical tiers of cusps on the beachface (Nolan, 1993). Plunging/collapsing waves will dominate with an Iribarren number of 0.7–1.95 and beach slopes will range from 0.04 to 0.12 with beach widths between 30 and 80 m.

4.1.3. Type 3: composite gravel beach (Fig. 10C)

The composite gravel beach is analogous to the 'mixed beaches' identified in the UK (e.g. Coates and Mason, 1998) and was first identified in the literature by Carter and Orford (1993). It is composed of a two-part profile due to hydraulic sorting. The seaward component will have the lowest gradient ($\tan\beta = 0.03$–0.1) and be sand dominated. Spilling waves will form with a dissipative surf zone at low tide and a long-shore bar-trough system may develop. The landward component is gravel, with a gradient of $\tan\beta = 0.1$–0.15. A re-

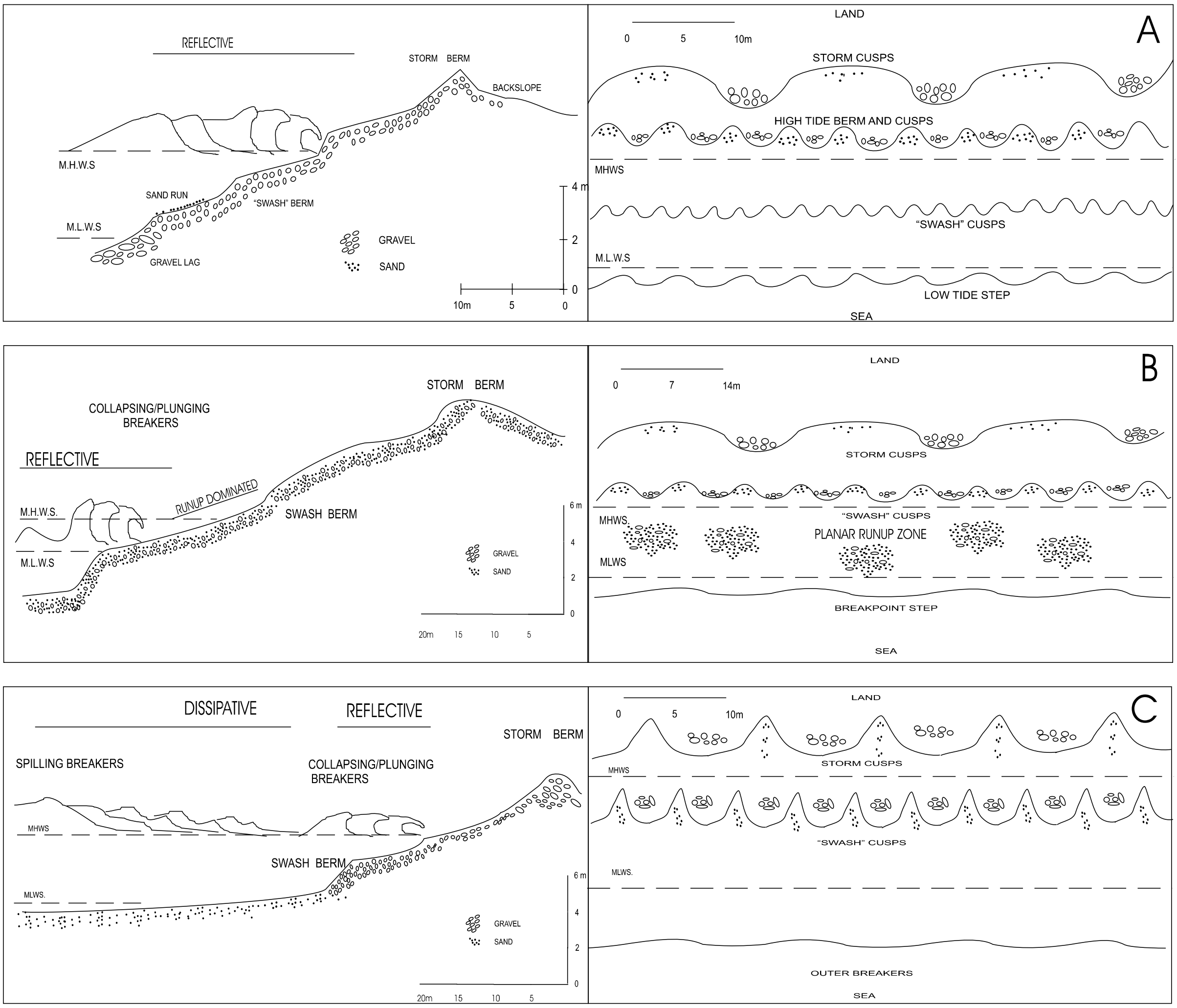

Fig. 10. Schematic representation of the three gravel beach types, in cross-section and plain view. The scale for each beach is different.(A) Pure gravel beach. Note the steep slope and plunging waves. Several sets of cusps are often present and a lag of coarse gravels forms at the toe of the beach. (B) MSG beach. Runup dominates with a planar swash zone and cusp development at the landward limit of runup. Sand and gravel are entirely intermixed, although some surficial sorting may develop. (C) Composite Gravel beach. A sandy intertidal zone dominates the lower profile, with a low slope. The change from sand to gravel is often marked by a distinct break in slope. Spilling breakers form at low tide and during storms.

flective regime dominates at high tide, and the permeability of the beachface and water table dynamics is likely to be controlled by the underlying substrate (Mason et al., 1997). The two zones intersect at a distinct break in slope. Beach widths may vary from less than 20 m to over 60 m, not including the low-tide surf zone. Cuspate morphology can develop on the gravel berm, which may also exhibit strong sediment sorting (e.g. Orford, 1975; Sherman et al., 1993). Under extreme storm conditions spilling breakers develop and the storm berm may be overtopped. Steep high-energy waves, which do not overtop the storm berm, can lead to seaward movement of the gravel component and the development of a break point bar (Orford, 1977). Once the waves are breaking upon the gravel berm plunging waves will dominate, with Iribarren values of 0.5–1.8.

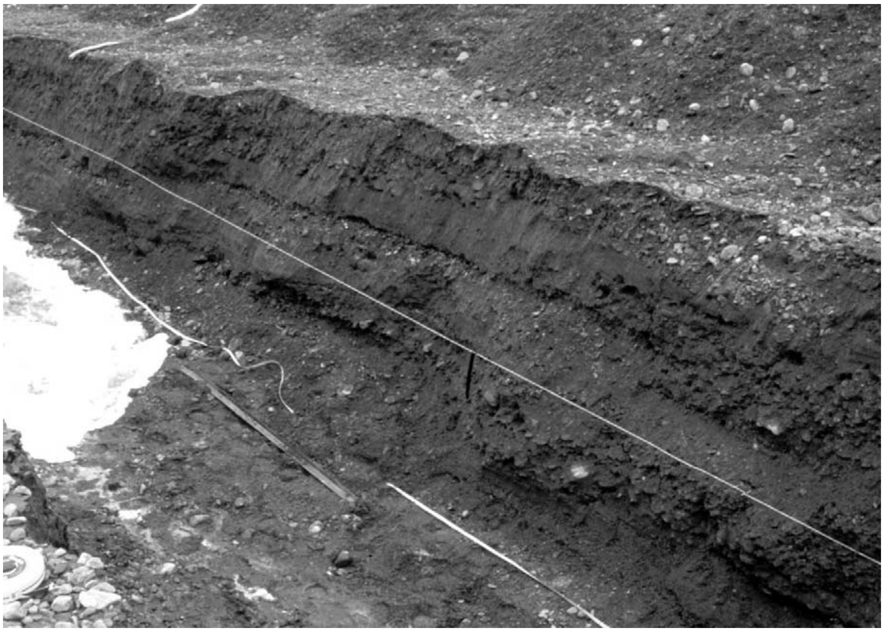

Fig. 11. MSG beach internal sediments, Orongorongo, New Zealand. Gravel and sand are entirely mixed at depth throughout the beach. This sediment pit extends from mid- to high tide at this site.

4.2. Morphodynamic implications

There is further evidence to suggest that the hydrodynamic regimes on these three gravel beach types will be different. The process of swash infiltration and beach permeability is one example. Gravel beaches have often been assumed to be highly permeable (Bluck, 1967). This assumption forms a basis for the mechanism of slope development under swash asymmetry (Quick, 1991). This mechanism has been shown to be problematic on sandy beaches, where the levels of infiltration required to develop a predominantly onshore sediment transport system do not exist (Masselink and Li, 2001). On coarse beaches (>1.5 mm) levels of infiltration will be sufficient to develop a dominant onshore swash transport system (Masselink and Li, 2001). However, field studies from a composite gravel beach show that the water table response is controlled by the underlying sand apron, despite the open-work nature of the surface gravels (Mason et al., 1997). If, as Carter and Orford (1984) state, the permeability of a gravel beach decreases as the sand content increases, leading to the development of lower slopes, then numerical approaches such as Masselink and Li (2001) will need to take into account sediment size range, as well as the mean grain size. Therefore, the assumption of high permeability is dependent upon the specific characteristics of the gravel beach being studied. This is a very important consideration in applied studies and in numerical modelling of sediment transport (e.g. Coates and Mason, 1998). The evidence from this research is that pure gravel beaches are highly permeable, allowing the development of a linear relationship between grain size and slope. Neither the MSG or the composite gravel beaches show this relationship which suggests that other mechanisms may be more important.

Gravel beaches are also considered to be highly reflective (Carter and Orford, 1984). The reflective nature of gravel beaches is very important in the generation of edge waves and cuspate morphology (Sherman et al., 1993). Due to the development of cusps, the reflective nature of gravel beaches has implications for their long-term stability. During storms, beaches with well developed cusps can be prone to erosion by overwash, particularly landward of cusp embayments (Carter and Orford, 1984). However, field measurements on a composite gravel beach have shown that the reflection of swell waves can fluctuate between 20 and 85% of incident wave energy depending upon tidal state (Mason et al., 1997). At high tide, once waves break on the gravel berm, the amount of reflection increases (Mason et al., 1997). Changes in wave reflection were only observed in the swell component, with reflection of the wind wave component remaining constant at 20–30% of total wave energy throughout the tidal cycle (Mason et al., 1997). Applying this finding to other gravel beach types suggests that pure gravel beaches, and MSG beaches, will be reflective throughout the tidal cycle due to their steeper active profile slopes. However, Powell (1990) monitored the reflection from a pure gravel beach in a physical modelling experiment and found that reflection remained constant at 10%, suggesting that wave dissipation is a function of surface roughness rather than permeability. Understanding these differences between beach types will be important for coastal management and protection.

The results suggest that the greatest similarity in morphology and process regime is between pure gravel and MSG beaches. This may be due to the lack of surf zone development on both beach types, and the pre-dominance of cuspate morphology. On composite gravel beaches it has been shown that spilling waves are responsible for storm beach modification (Orford, 1975). In contrast, under storm conditions MSG beaches are known to be dominated by a single breakpoint due to the controlling effect of the beachface step (Kirk, 1980). It is also unlikely that spilling waves will form on pure gravel beaches due to their steep slopes and the lack of offshore bar development. Therefore, the storm response of composite gravel beaches will be different to that of pure gravel and MSG beaches.

5. Conclusions

This model provides a method for discriminating between the main types of gravel beach and their morphodynamic regimes. Although the model presented here enables the distinction of three separate gravel beach types, pure gravel, MSG and composite, it is not possible to determine if the three types are part of a continuum. On sandy beaches the exact state of a beach will be a function of the instantaneous process regime, sediment transport patterns and antecedent history. However, on gravel beaches there has been no evidence to suggest that, over instantaneous to event scales, switching between these three states occurs. It is more probable that within-state variation will occur, such as cycles of storm erosion and post storm recovery as observed by Sherman (1991). What controls the development of one beach type over another is yet to be determined; however, certain factors such as sediment supply and antecedent geology are likely to be significant. It is almost certain that each type will have a different process signature and morphodynamic behavior. This suggests that the three types will also require different management strategies and be applicable in different coastal protection applications.

The benefits of this scheme are that it enables simple, field based, visual discrimination of gravel beaches into one of three main types. Through the measurement of some basic parameters this initial visual assessment can be confirmed. Through the use of this scheme greater integration of studies in different locations will be possible. This is important as there is a lack of morphodynamic understanding of gravel beaches. Further development of this model should include the consideration of wave climate, tidal range, sediment supply and sediment transport.

Acknowledgements

The authors would like to thank Rob Brander (UNSW) for help and encouragement in the field, and the University of Canterbury for use of their field station. Fieldwork support was provided by Nancy Bertler (VUW). R.J. is grateful to the Vice Chancellors Committee, New Zealand, and the Commonwealth Scholarship Scheme for financial assistance. Reviews by D. Sherman and A. Short were instrumental in improving the manuscript.

David Kennedy (VUW) read an earlier draft of this paper and his comments were much appreciated.

References

Anthony, E.J., 1998. Sediment-wave parametric characterization of beaches. J. Coast. Res. 14, 347–352.

Bascom, W.N., 1951. The relationship between sand size and beach-face slope. Trans. Am. Geophys. Union 32, 866–874.

Battjes, J.A., 1974. Surf similarity. Proc. 14th Conference on Coastal Engineering, American Society of Civil Engineers, pp. 466–480.

Bauer, B.O., Greenwood, B., 1988. Surf-zone similarity. Geogr. Rev. 78, 137–147.

Bluck, B.J., 1967. Sedimentation of beach gravels: examples from south Wales. J. Sediment. Petrol. 37, 128–156.

Brander, R.W., 1999. Field observations on the morphodynamic evolution of a low-energy rip current system. Mar. Geol. 157, 199–217.

Caldwell, N.E., Williams, A.T., 1985. The role of beach profile configuration in the discrimination between differing depositional environments affecting coarse clastic beaches. J. Coast. Res. 1, 129–139.

Carr, A.P., 1971. Experiments on longshore transport and sorting of pebbles: Chesil beach England. J. Sediment. Petrol. 41, 1084.

Carter, R.W.G., Orford, J.D., 1984. Coarse-clastic barrier beaches – a discussion of their distinctive dynamic and morphosedimentary characteristics. Mar. Geol. 60, 377–389.

Carter, R.W.G., Orford, J.D., 1988. Conceptual model of coarse clastic barrier formation from multiple sediment sources. Geogr. Rev. 78, 221–239.

Carter, R.W.G., Orford, J.D., 1993. The morphodynamics of coarse clastic beaches and barriers: a short- and long-term perspective. J. Coast. Res. SI 15, 158–179.

Carter, R.W.G., Jennings, S.C., Orford, J.D., 1990. Headland erosion by waves. J. Coast. Res. 6, 517–529.

Chappell, J., Eliot, I.G., 1979. Surf-beach dynamics in time and space – an Australian case study, and elements of a predictive model. Mar. Geol. 32, 221–250.

Coates, T.T., Mason, T., 1998. Development of predictive tools and design guidance for mixed beaches. HR Wallingford Report, TR 56.

Engelman, L. 1998. Discriminant Analysis. Systat Vol. 9, SPSS Inc.

Forbes, D.L., Taylor, R.B., Orford, J.D., Carter, R.W.G., Shaw, J., 1991. Gravel barrier migration and overstepping. Mar. Geol. 97, 305–313.

Forbes, D.L., Orford, J.D., Carter, R.W.G., Shaw, J., Jennings, S.C., 1995. Morphodynamic evolution, self organisation and instability of coarse clastic barriers on paraglacial coasts. Mar. Geol. 126, 63–85.

Jennings, S., Orford, J.D., Canti, M., Devoy, R.J.N., Straker, V., 1998. The role of relative sea level rise and changing sediment supply on Holocene gravel barrier development: the example of Porlock, Somerset, UK. Holocene 8, 165–181.

Kemp, P.H., 1961. The relationship between wave action and beach profile characteristics. Proc. Seventh Conference on Coastal Engineering, American Society of Civil Engineers, pp. 262–277.

Kirk, R.M., 1975. Aspects of surf runup processes on mixed sand and gravel beaches. Geogr. Ann. 57 (A 1/2), 117–133.

Kirk, R.M., 1980. Mixed sand and gravel beaches: morphology, processes and sediments. Prog. Phys. Geogr. 4, 189–210.

Komar, P.D., 1998. Beach Processes and Sedimentation. Prentice-Hall, Englewood Cliffs, NJ, 544 pp.

Krumbein, W.C., 1941. Measurement and geological significance of shape and roundness of sedimentary particles. J. Sediment. Petrol. 11, 64–72.

Long, A.J., Hughes, P.D.M., 1995. Mid and late Holocene evolution of the Dungeness foreland, UK. Mar. Geol. 124, 253–271.

Lorang, M., Namikas, S.L., McDermott, J.P., Sherman, D.J., 1999. El Niño storms and the morphodynamic response of two cobble beaches. Proc. Coastal Sediments '99. American Society of Civil Engineers, pp. 922–937.

Mason, S.J., Hansom, J.D., 1989. A Markov model for beach changes on the Holderness coast of England. Earth Surf. Process. Landf. 14, 731–743.

Mason, T., 1997. Hydrodynamics and Sediment Transport on a Macro Tidal, Mixed (Sand and Shingle) Beach. PhD Thesis, University of Southampton, Southampton.

Mason, T., Voulgaris, G., Simmonds, D.J., Collins, M.B., 1997. Hydrodynamics and sediment transport on composite (mixed sand/shingle) and sand beaches: A comparison. Coastal Dynamics, American Society of Civil Engineers, pp. 48–57.

Masselink, G., Li, L., 2001. The role of swash infiltration in determining the beachface gradient: a numerical study. Mar. Geol. 176, 139–156.

Masselink, G., Short, A.D., 1993. The effect of tide range on beach morphodynamics and morphology: a conceptual beach model. J. Coast. Res. 9, 785–800.

McKay, P.J., Terich, T.A., 1992. Gravel barrier morphology: Olympic National Park, Washington State, USA. J. Coast. Res. 8, 813–829.

Nicholls, R.J., Wright, T.P., 1991. Longshore transport of pebbles: Experimental estimates of K. Proc. Coastal Sediments '99. American Society of Civil Engineers, pp. 920–933.

Nicholls, R.L., Webber, N.B., 1987. The past, present and future evolution of Hurst Castle Spit, Hampshire. Prog. Oceanogr. 119–137.

Nolan, T.J., 1993. Beach Cusps as Indicators of Sea-level. Unpubl. MSc Thesis, Canterbury University, Canterbury.

NZNA, 2000. New Zealand Nautical Almanac. Land Information New Zealand.

Orford, J.D., 1975. Discrimination of particle zonation on a pebble beach. Sedimentology 22, 441–463.

Orford, J.D., 1977. A proposed mechanism for storm beach sedimentation. Earth Surf. Process. Landf. 2, 381–400.

Orford, J.D., Carter, R.W.G., Jennings, S.C., Hinton, A.C., 1995. Processes and timescales by which a coastal gravel-dominated barrier responds geomorphologically to sea-level rise: Story Head Barrier, Nova Scotia. Earth Surf. Process. Landf. 20, 21–37.

Orford, J.D., Carter, R.W.G., Jennings, S.C., 1996. Control domains and morphological phases in gravel dominated coastal barriers of Nova Scotia. J. Coast. Res. 12, 589–604.

Pickrill, R.A., Mitchell, J.S., 1979. Ocean wave characteristics around New Zealand. N.Z. J. Mar. Freshw. Res. 13, 501–520.

Powell, K.A., 1988. The dynamic response of shingle beaches to random waves. In: Edge, B. (Ed.), Twenty-first Coastal Engineering Conference, Spain. American Society of Civil Engineers, pp. 1763–1773.

Powell, K.A., 1990. Predicting short term profile response for shingle beaches. HR Wallingford Report, SR 219.

Quick, M.C., 1991. Onshore-offshore sediment transport on beaches. Coast. Eng. 15, 313–332.

Quick, M.C., Dyksterhuis, P., 1994. Cross shore transport for beaches of mixed sand and gravel. International Symposium: Waves – Physical and Numerical Modelling. Canadian Society of Civil Engineers, pp. 1443–1452.

Ranasinghe, R., Pattiaratchi, C., Masselink, G., 1999. A morphodynamic model to simulate the seasonal closure of tidal inlets. Coast. Eng. 37, 1–36.

Sanders, D., 2000. Rocky shore-gravely beach transition, and storm/post storm changes of a Holocene gravely beach (Kos Island, Aegean Sea): Stratigraphic significance. Facies 42, 227–244.

Shepard, F.P., 1963. Submarine Geology. Harper and Row, New York.

Sherman, D.J., 1991. Gravel beaches. Nat. Geogr. 7, 442–452.

Sherman, D.J., Orford, J.D., Carter, R.W.G., 1993. Development of cusp-related, gravel size and shape facies at Malin Head, Ireland. Sedimentology 40, 1139–1152.

Short, A.D., 1979. Three-dimensional beach-stage model. J. Geol. 87, 553–571.

Short, A.D., 1999. Handbook of Beach and Shoreface Morphodynamics. Wiley, New York.

Shulmeister, J., Kirk, R.M., 1993. Evolution of a mixed sand and gravel barrier system in North Canterbury, New Zealand, during Holocene sea-level rise and still-stand. Sediment. Geol. 87, 215–235.

Shulmeister, J., Kirk, R.M., 1997. Holocene fluvial-coastal interactions on a mixed sand and sand and gravel beach system, North Canterbury, New Zealand. Catena 30, 337–355.

Soons, J.M., Shulmeister, J., Holt, S., 1997. The Holocene evolution of a well nourished gravelly barrier and lagoon complex, Kaitorete 'Spit', Canterbury, New Zealand. Mar. Geol. 138, 69–90.

Stapleton, K., Mason, T., Coates, T.T., 1999. Sub-tidal resolution of beach profiles on a macro tidal shingle beach. Proc. Coastal Sediments '99. American Society of Civil Engineers, pp. 885–893.

StatSoft, 2001. Electronic Statistics Textbook. StatSoft, Tulsa, OK. http://www.statsoft.com/textbook/stathome.html.

Sunamura, T., Aoki, H., 2000. A field experiment of cusp formation on a coarse clastic beach using a suspended video-camera system. Earth Surf. Process. Landf. 25, 329–333.

Williams, A.T., Caldwell, N.E., 1988. Particle size and shape in pebble beach sedimentation. Mar. Geol. 82, 199–215.

Wright, L.D., Short, A.D., 1984. Morphodynamic variability of surf zones and beaches: a synthesis. Mar. Geol. 56, 93–118.

Wright, L.D., Thom, B.G., 1977. Coastal depositional landforms: a morphodynamic approach. Prog. Phys. Geogr. 1, 412–459.

Wright, L.D., Short, A.D., Green, M.O., 1985. Short-term changes in the morphodynamic states of beaches and surf zones: an empirical predictive model. Mar. Geol. 62, 339–364.

Zenkovich, V.P., 1967. Processes of Coastal Development. Oliver and Boyd, Edinburgh.