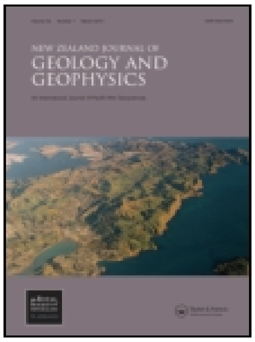

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Relationships between grain size, size-sorting, and foreshore slope on mixed sand - shingle beaches

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RELATIONSHIPS BETWEEN GRAIN SIZE, SIZE-SORTING, AND FORESHORE SLOPE ON MIXED SAND-SHINGLE BEACHES

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ABSTRACT

The variation of mean grain size (Mzϕ), sorting (σ_I), and beach face slope over mixed sand shingle beaches at two areas along the east coast, South Island, New Zealand, is analysed in order to determine the nature of the relationships between these three variables. The study is confined to mean grain sizes between 0·25 and 16·0 mm, and the sorting and slope values associated with this range of sizes. Trend analysis of the data has been performed by fitting curves with the aid of a computer.

As distinct from the linear average relationship betweeen size and slope distinguished by many workers, it is demonstrated that for given beaches curvilinear trends in size/sorting are reflected in slope/size relationship. Thus, the best sorted sediments are found to be associated with the steepest gradients on the curves, while zones of poor sorting are associated with "plateaus" in the size/slope trend.

It is suggested that size is the primary control of sorting trends in the sediments examined whilst hydraulic effects (wave action, etc.) contribute to variability, or spread of the data around the trend. Since size and sorting exert a primary influence on beach face slope through permeability, it is further suggested that, for the study beaches at least, trends in the size/slope relationship clearly reflect the characteristic local distributions of size and sorting.

INTRODUCTION

It is well known that a relationship exists between the foreshore slope of a beach (beach-face slope; shore-face slope) and the average size grade of the foreshore sediment. Increasing slope angles are associated with increasing particle dimensions; gravel (shingle) beaches are steeper than sand beaches. While size of material, through permeability, apparently exerts a primary control on foreshore slope (Inman and Bagnold, 1966; Shepard, 1963, p. 170), at least two other factors can provide steeper or gentler slopes for any given average grain diameter: (a) the degree of exposure of the beach, and (b) whether beach erosion or accretion is taking place. Firstly, protected beaches have steeper slopes than more exposed beaches (Wiegel, 1964, p. 358), and secondly, episodes of erosion result in a "combing down" of the beach face to lower slopes, while periods of foreshore fill result in steeper slopes. It is evident then that although foreshore slope is dependent on particle size in the first instance, there are other controls which make it impossible to predict precisely what the slope will be for any given average grain diameter for all beaches.

The relationships between slope and grain size are best known for sand beaches, and there are numerous graphical presentations relating average grain size (mean or median) and slope or gradient for diameters up to about 1·2 mm (e.g., Bascom, 1951; Emery and Gale, 1951; Wiegel, 1964, p. 359; U.S. Army Corps of Engineers, 1966, p. 158). There are, however, no equivalent presentations for shingle beaches, although individual slope values have been given by some authors (e.g., King, 1959; p. 322; Guilcher, 1958, p. 80; Zenkovitch, 1967, p. 269). The same is true for beaches made up of a mixture of sand and shingle. Intuitively, one would expect the slope/size relationship to be much more complex on mixed beaches than on pure sand or pure shingle beaches. Indeed, while noting that "there are significant differences between the morphology and dynamics of sandy beaches and those of coarser material (shingle and pebbles)" Zenkovitch (1967, p. 271) argues that "the dynamics of mixed beaches consisting of coarse and fine material (shingle and sand) are the most complicated". It is with these latter types of beaches that the present paper is concerned.

Because of the complex nature of mixed sand-shingle beaches, factors additional to average grain diameter, exposure, and the beach condition at the time of sampling (mentioned above) must also be taken into account. For instance, other material factors such as shape, roundness, and imbrication of the sediment (Bluck, 1967) as well as skewness and the degree of sorting would appear significant. Sorting is likely to be especially important on a mixed sand-shingle beach, where, because of the large variety of sizes present, the average grain diameter can disguise a wide spread in the sampled material. Thus, in the present investigation three variables—(a) foreshore slope; (b) mean grain size; and (c) degree of sorting of the sediment—have been selected for consideration.

In recent years much attention has been paid to the significance of the degree of sorting of beach sediments. A general correspondence between grain size and sorting has been found by numerous investigators (e.g., Inman, 1949; Griffiths, 1951; Folk and Ward, 1957). This correspondence has been interpreted in two different ways. Inman (1949) examined sorting in the light of fluid mechanics and concluded that degree of bottom roughness, settling velocity, and threshold velocity were the three primary controlling factors. That is, sorting can be attributed to hydraulic forces acting in the beach environment. Folk and Ward (1957), on the other hand, postulated a "source area effect" to account for the sinusoidal relationship between size and sorting they encountered. They argued that two population "end members" in the sand and gravel sizes accounted for two strong minima of best sorting whilst poorer sorting in the intermediate sizes resulted from mixing of the two main population constituents present. Blatt (1958, *in* Folk, 1962) confirmed this sinusoidal trend in sands and gravels from New Jersey beaches, the modes of best sorting occurring at 1 to 3 ϕ and at -3 ϕ units. Thus, in contrast to Inman, Folk (1962, pp. 237–8) has suggested that the first order control on sorting is mean size and that hydraulic factors (e.g., wave action) exert only a second order effect.

If Folk's hypothesis is correct, it is possible that on beaches where a large range of sediment sizes is present, characteristic grain size/foreshore slope patterns may exist as a response to grain size / sorting variations. To be more specific, if there exists a characteristic curvilinear relationship between average grain size and size-sorting, it is reasonable to expect an equally characteristic effect on foreshore slope, with sorting being dependent on size, and slope dependent on size and sorting.

It is therefore the primary purpose of this paper to examine the relationships between size/slope and size/sorting in the light of this hypothesis, using data from some mixed sand-shingle beaches located in two areas along the east coast, South Island, New Zealand. A second purpose is to evaluate qualitatively any similarities or differences in these relationships as displayed by the beaches in the two areas studied. This study is limited to mean grain sizes between 0·25 mm and 16·0 mm, and the sorting and slope values associated with this range of sizes. It does not cover the whole range of sizes of material occurring on both beaches.

CONCEPTUAL FRAMEWORK

The utility of a conceptual framework for beach studies has been demonstrated by Krumbein (1963). The framework utilised in this study is illustrated in Fig. 1. This arrangement makes more explicit the relationships among the elements mentioned previously. Foreshore slope is seen as the

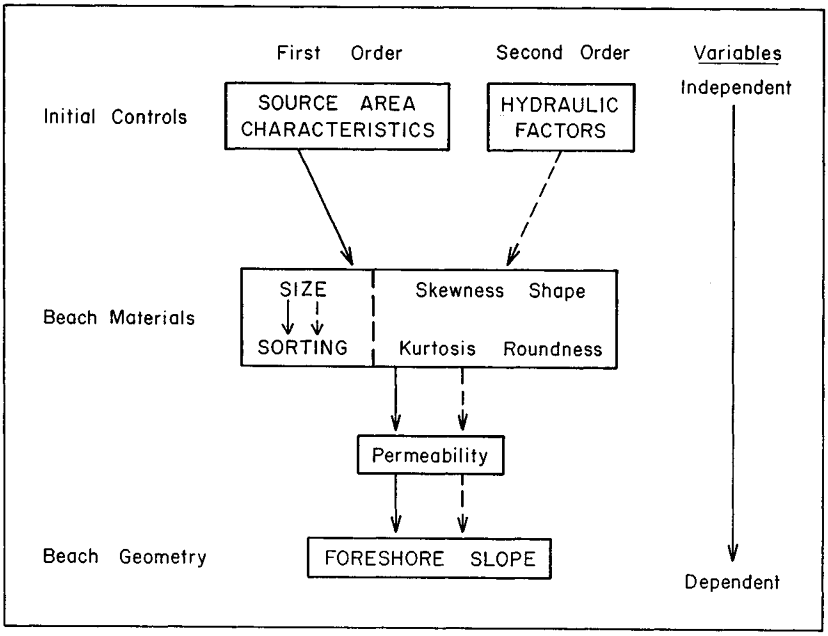

FIG. 1—Conceptual model relating initial controls, material factors, and foreshore slope to show levels of dependency. First order controls indicated by solid arrows. Second order controls indicated by dashed arrows.

ultimate response element; the dependent variable influenced by all the factors above it. The level of dependency increases from the initial controls through the material factors to foreshore slope. In this arrangement source area characteristics and hydraulic factors are the initial controls. The patterns of their respective influences can be considered separately.

Firstly, the source area contribution—provenance, erosion, and weathering, and provision of material to the shore—can be regarded in this context as a constant. Following Folk (1962) the beach material properties itemised in the second row in Fig. 1 closely reflect source area characteristics. The properties include particle size parameters mean grain size, size-sorting, skewness and kurtosis, as well as particle form characteristics, e.g., shape, roundness, shape-sorting, etc. Of these, only mean grain size and size-sorting are investigated here. The small arrow from size to sorting indicates the dependence of sorting on size. Permeability intervenes between these material factors and foreshore slope; it is included for the sake of completeness, as it is via permeability that size and sorting influence foreshore slope. Krumbein and Monk (1942, *in* Shepard, 1963, fig. 54, p. 113) have demonstrated that permeability varies with the square of the geometric mean grain diameter and in an inverse exponential fashion with degree of sorting. In the above manner source area characteristics are reflected in foreshore slope characteristics, via grain size and sorting and permeability as indicated by the solid arrows in Fig. 1. It is argued in this paper that the *gross* foreshore slope patterns reflect these steps.

Secondly, hydraulic factors must also be considered in this framework. Although shown in Fig. 1 as an initial control, hydraulic factors are regarded as having a second order influence as indicated by the dashed arrows. The overall energy environments of the two areas described in this paper are similar and can be roughly regarded as constant. However, considerable variability within this broad pattern exists both in time and space, with significant fluctuations in wave height, period, angle of approach, etc., being characteristic. It is anticipated that such variability in hydraulic conditions will be reflected, not so much in the gross size/slope or size/sorting patterns, but in their *variability* or spread. That is, fluctuations in hydraulic conditions will be represented in the variability in size/sorting values, which in turn will be reflected in foreshore slope/size variability.

DESCRIPTION OF BEACHES STUDIED

Beaches composed of predominantly greywacke-derived sediments are common between Cloudy Bay and Oamaru on the east coast, South Island (Fig. 2a). Beaches in two areas along this coast, Kaikoura, and Canterbury Bight, were selected for study. There are certain differences in the extent and setting of the beaches in these two areas. The mixed sand-shingle beach of the Canterbury Bight is continuous for 84 miles from Banks Peninsula to Timaru. This beach has recently been investigated by Kirk (1967). In the Kaikoura area the two beaches studied are less extensive, that between the Kahutara River and South Bay being 5·5 miles long and that between Kaikoura township and Mangamaunu being 10 miles long. Although these

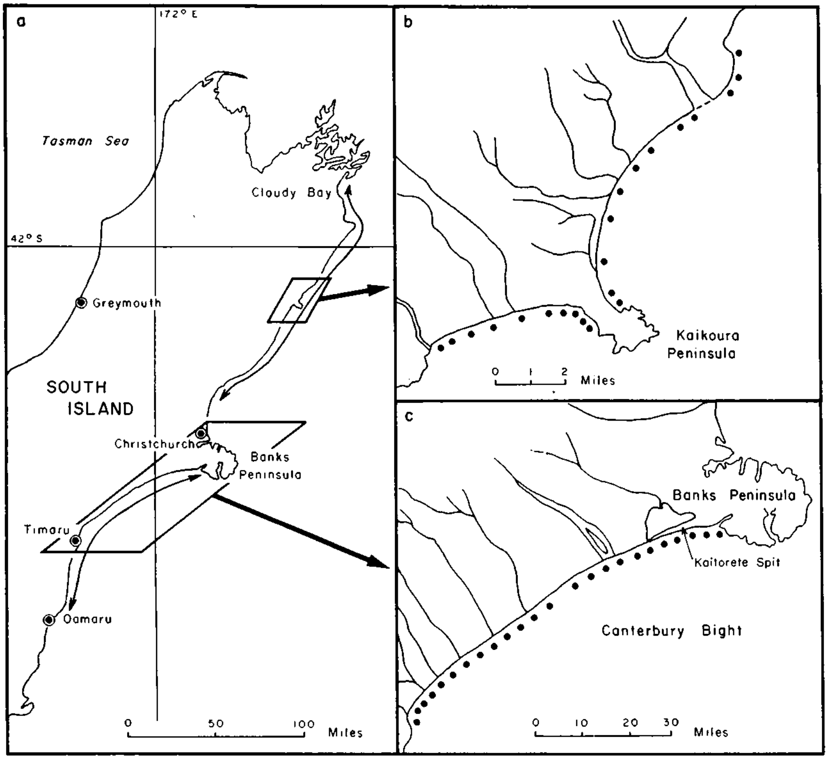

FIG. 2—Location of Kaikoura and Canterbury Bight beaches along east coast, South Island, New Zealand. a—Distribution of greywacke-derived beach sediments indicated by small arrows. b, c—Positions of sampling sites shown by dots.

two beaches possess differences in detail (McLean, pers. comm.) they are in general terms similar, and for the purposes of this investigation data from both have been treated jointly. The immediate hinterlands of the Canterbury Bight and Kaikoura beaches are also different. Along the Canterbury Bight three coastal elements can be distinguished: (a) a wave built barrier (Kaitorete Spit) in the north; (b) a narrower, lower barrier in the south near Timaru; and (c) a central section of high, eroding, alluvial cliffs. At Kaikoura, on the other hand, the present beaches are backed mainly by low beach ridges or very recent alluvium.

Similarities between the two areas are however more apparent and important from the point of view of the present study:

(1) Both beaches form the edges of plains made up of confluent fans, delta-fans, and alluvium brought down from the main greywacke mountain blocks in the South Island (Jobberns, 1928; Speight, 1950).

(2) Both coasts follow the general north-east trend of the east coast, South Island, and therefore face towards the south-east.

(3) Both beaches are exposed to highly variable and often severe wave action emanating from storm centres in the Pacific Ocean. The prevailing waves approach from the south-east, but there is also a strong north-east component (McLean, 1967). Wave heights average about 1–2 m at the shore and storm waves are typically 3–5 m high. Such conditions result in highly turbulent swash-backwash on the foreshore.

(4) Both beaches can be described as mixed sand-shingle beaches. Apart from certain localities the different size grades of sediment are mixed, both along and across the shore. There is no significant lateral trend in size grades along the Canterbury Bight (Kirk, 1967, p. 65), while at Kaikoura, although trends exist, they are very complex ones (McLean, pers. comm.). Moreover, there is no distinct break or discontinuity in grain size or slope angle between sand and shingle across the beach as described by other authors (e.g., King, 1959, p. 163); Inman and Bagnold, 1966, p. 530).

(5) Textural analysis has revealed that both beach deposits are "submature" in Folk's terminology (Folk, 1965, pp. 102–6). Although an oversimplification, the pebble fraction combines good sorting for size, shape, and roundness, whilst the sand fraction has good size-sorting, but only poorly developed roundness.

(6) Beach profiles surveyed normal to the shore in both areas have revealed characteristics of both typical sand beach and typical shingle beach forms as well as combinations of both types. Profile changes monitored over several months have indicated minimum amounts of nett change, i.e., there is a small range in envelope curves, although the variation in profiles between surveys may sometimes be large. This latter variability is a response to the rapid changes in wave conditions noted above.

METHODS

Sampling sites were established at the localities shown in Fig. 2b and 2c. At each locality a sample of material weighing approximately 100–2,000 g was collected from the "reference point" (Bascom, 1951) in the mid-tide zone after the slope of the foreshore had been measured, in degrees, by Abney level. Twenty-four stations spaced about 3 miles apart were set up along the Canterbury Bight. At these, materials and slopes were sampled three times between December 1966 and May 1967. In addition, a number of backshore samples were obtained for size/sorting analysis. At Kaikoura, 22 stations were established at intervals of about 0·8 miles and 0·5 miles for the beaches to the north and south of the Kaikoura Peninsula respectively. Repeated sampling was at monthly intervals between March 1966 and December 1966.

In the laboratory, all samples were treated by standard techniques of washing, oven-drying, and, where necessary, splitting. Materials coarser than $\frac{1}{8}$ in. were sieved by hand through $2\frac{1}{2}$, $1\frac{1}{2}$, 1, $\frac{3}{4}$, $\frac{3}{8}$, $\frac{3}{16}$, and $\frac{1}{8}$ in. screens and the remainder were shaken for 15 minutes in an "Endrock" sieve shaker through the B.S.C.P. screens of approximately $\frac{1}{2}\ \phi$ intervals. The weight percentage retained on each sieve was converted to a percentage of total sample weight and plotted cumulatively on log normal graph paper. Frequency was plotted on the ordinate (arithmetic scale) and grain size on the abscissa (log scale). An arithmetic overlay for phi (ϕ) units was included on the horizontal scale to facilitate computation of grain size parameters.

The relevant percentile values were abstracted from the size-frequency distributions and the Graphic Mean Diameter (M_z) and Inclusive Graphic Standard Deviation (σ_I) or sorting as defined by Folk (1965, pp. 45–6) of each distribution was calculated on the IBM 1620 computer, University of Canterbury. These values together with foreshore slope values were used to plot the frequency polygons and scattergrams (Figs. 3, 4, 6). Further analyses of the nature of the relationships between mean grain size, sorting, and foreshore slope were carried out on the University of Otago's IBM 360 computer, using size as the independent variable (X), and slope in one case and sorting in the other as dependent variables (Y). Polynomial curves of orders 1 to 6 were fitted to each data set (size/slope; size/sorting) and graphical plots of the best fitting curves were drawn from the print out of predicted Ys for each X.

RESULTS

Frequency Distributions

Frequency distributions of size, slope, and sorting, for the two areas, separately and combined, are shown as polygons and cumulative curves in Fig. 3. These curves are useful (a) for comparing the patterns among the elements themselves (size and slope, size and sorting) and between the Canterbury Bight and Kaikoura areas; (b) as a descriptive summary of one geometrical property and two sedimentary parameters for mixed sand-shingle beaches; and (c) as a first stage in the analyses of the regularities and irregularities in the relationships between the variables.

Mean Grain Size

A comparison between the size frequency distributions of foreshore materials is shown in Fig. 3a. It can be clearly seen that there are marked differences in the range of mean size grades occurring on the two beaches. The median mean size value for Kaikoura was $-0{\cdot}35\ \phi$ whilst that for Canterbury was $-1.15\ \phi$. Significantly, in the light of Folk's suggestion (1962, 1965) concerning the size/source area effect, both the frequency distributions are markedly bimodal. The modes, however, are offset with maximum frequencies associated with different mean sizes in the two cases. Fig. 3a (1) shows that the Canterbury Bight modes occur at $0{\cdot}2\ \phi$ (coarse sand) and $-3{\cdot}30$ units (pebbles) and that these values are approximately $0{\cdot}6\ \phi$ and $2{\cdot}1\ \phi$ units coarser than those for Kaikoura. The Kaikoura modes occur in the medium-coarse sand and granule size grades. Thus it is clear that the Canterbury Bight samples are generally coarser than Kaikoura samples.

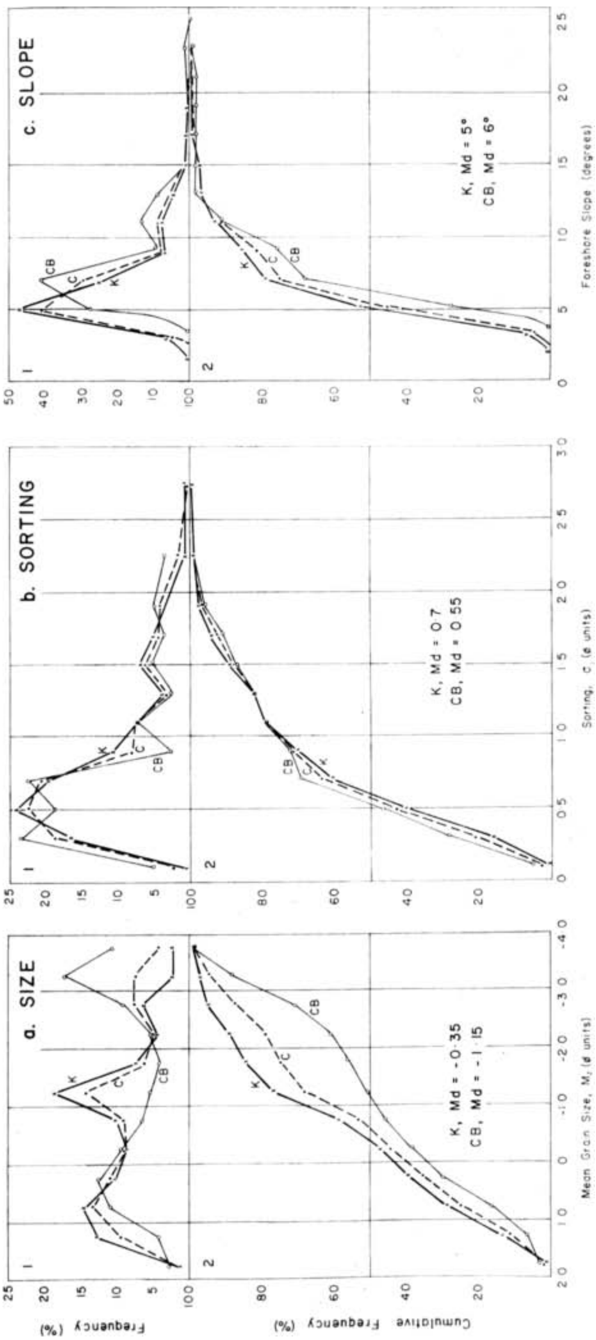

FIG. 3—Grain size, sorting, and foreshore slope frequency distributions for Kaikoura (K) and Canterbury Bight (CB) beaches and combined data (C). 1—Frequency (%) polygons. 2—Cumulative frequency (%). a—Mean grain size frequency per 0·5 ϕ units. b—Sorting frequency per 0·2 ϕ units. c—Foreshore slope frequency per 2°.

Some 68% of the total from Kaikoura have a mean size in the sand size fraction, whilst for Canterbury the figure is only 48%. It is to be remembered that only mean grain sizes less than $M_z\phi = -4$ were considered in this investigation.

Sorting

These marked differences in mean particle diameters might be expected to result in equally clear variations in sorting values for both beaches, but Fig. 3b indicates that this is not so. Median sorting values in each case lie in Folk's moderately well sorted category, while 34% and 22% of the Canterbury Bight and Kaikoura samples respectively are very well sorted. Poorly sorted samples ($\sigma_I > 1{\cdot}0\ \phi$ units) composed about 25% of the combined data. It can be seen in patterns of the frequency distributions in Fig. 3a (1) that there is also a tendency for bimodality. For both beaches a very strong mode occurs around $0{\cdot}5\ \phi$ units (well to moderately well sorted) and a much weaker mode around $1{\cdot}5\ \phi$ units (poorly sorted). It will be shown later (Fig. 5) that the first of these modes relates to the medium sand and pebble fractions, whilst the second is grouped with the coarse sand - granule size grades. It is this latter group that Folk (1962) suggests is a mixture of two end member size populations in the sand and pebble fractions.

Thus, the data exhibit significant differences between the two study areas in respect to size distributions but reveal a general correspondence in sorting values. These results are not surprising in view of the similar mineralogies of the beaches and the high energy nature of the shores.

Foreshore Slope

The general similarity in the beach sediment properties measured is reflected, as predicted by the model, in the frequency distributions of foreshore slope as shown in Fig. 3c. It can be seen that slopes are not generally steep. The median slope for the Canterbury Bight was 6° whilst for Kaikoura the corresponding value was 5°. More than 80% of the measured slopes in both areas are under 10° whilst for the Kaikoura data it can be seen that half of the foreshore slopes were less than 5°.

However, the most notable feature of the distributions is their bimodal nature (Fig. 3c (1)). The secondary peak occurs in the 10°–12° region for both beaches and represents 9% and 12% of the observations at Kaikoura and Canterbury Bight respectively. There is thus a general correspondence between variations in the sedimentological properties measured and in the resulting foreshore geometry as gauged by the one property—foreshore slope. It was this preliminary agreement with the model outlined above that prompted more detailed analysis of the data.

Size/Sorting Relationships

A scattergram of the size and sorting values from the two beaches is shown in Fig. 4. It is important to note that the Canterbury data include samples from the backshore zone whilst the Kaikoura data do not. A notable feature of the scattergram is the wide ranges of both size and sorting

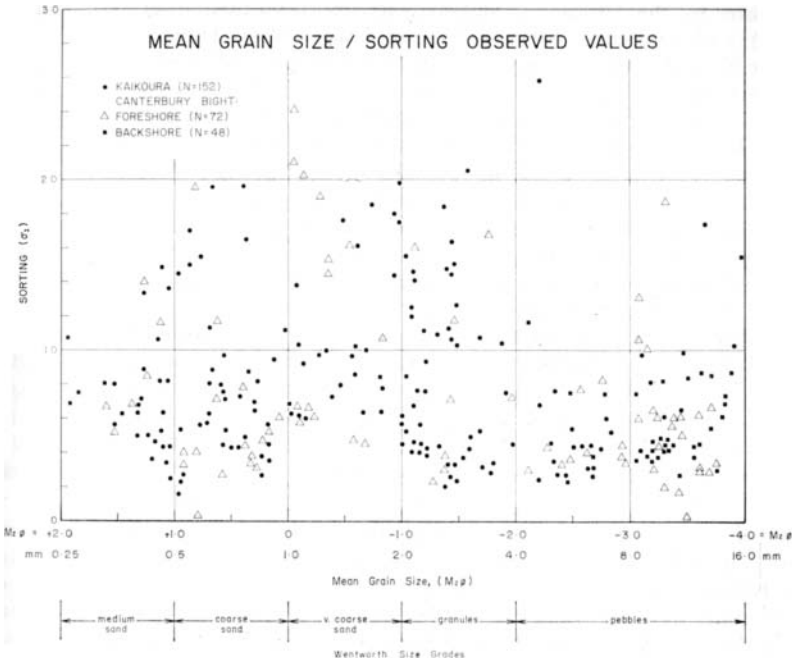

FIG. 4—Scattergram of observed mean grain size and sorting values of foreshore sediments from Canterbury Bight and Kaikoura beaches. Note, some backshore samples from Canterbury Bight are also included.

previously mentioned. Mean grain-size ranges from $-3{\cdot}75\ \phi$ to $1{\cdot}6\ \phi$ for the Canterbury foreshore data and from $-3{\cdot}90\ \phi$ to $1{\cdot}53\ \phi$ for Kaikoura. Canterbury Bight backshore samples range from $-3{\cdot}98\ \phi$ to $1{\cdot}95\ \phi$ and it can be seen that sorting values vary widely, the overall range for all samples being from $0{\cdot}03$ to $2{\cdot}58\ \phi$ units.

A second notable feature is that the data fall into two distinct groupings as previously noted. A strong size/sorting mode occurs in the region $-2{\cdot}5\ \phi$ to $-4{\cdot}0\ \phi$ whilst for grain-sizes less than this, sorting is more variable. This is consistent with the high energy nature of the beaches and the effects that this would have on the smaller grain-sizes, as predicted by the model.

A clear "tail" to the data is formed by the Canterbury Bight backshore data in the region $-3{\cdot}0\ \phi$ to $-4{\cdot}0\ \phi$ and it is noteworthy that at smaller sizes these samples are more uniformly sorted than the more frequently winnowed and mixed foreshore samples.

The results of curve-fitting on this data are presented in Fig. 5 and Table 1. Order 3 curves for both Kaikoura and Canterbury were indicated by F-tests to be the most significant for the data. These curves are similar in form to the sinusoidal size/sorting trend postulated by Folk (1962, 1965) and verified by Blatt (1958, *in* Folk, 1962). However, in the case of the Kaikoura data a more complex situation was indicated by the analysis. Table 1 shows that an Order 5 curve was only slightly less significant at the 0·01 level and gave additional explanation of the data variation. This curve has also been plotted as an aid to comparison.

It is clear that there are marked differences between the curves derived in this investigation and that proposed by Folk. Though the overall form is similar, i.e., the curves have two regions of best sorting with decreases away from these zones, the amplitude of the "mixed" zone between the sand and pebble modes is low. Further reference to Fig. 4 indicates that probably the most significant characteristic of this zone is not the decrease in sorting but rather the wide range that occurs, from very well sorted to very poorly sorted. Because of the high energy nature of the beaches this is the region where hydraulic effects on the grain-size distributions are most pronounced.

Another striking feature of Fig. 5 is the pronounced coarse "tail" of the Canterbury Bight curve. This is produced mainly by the backshore samples, but removal of these data from the procedure would not eliminate the tail nor alter the curve form significantly in any other region.

Of interest is the general correspondence of fit between the Canterbury and Kaikoura data, apart from the coarser values. The Order 5 curve for the Kaikoura data also corresponds to both Order 3 curves over the major portion of the graph except that it has secondary inflexions at the extremities. It is these zones for which predictions are the least reliable since data are few.

Table 1 also indicates the results of curve fitting to the combined data from both study areas. Significantly, the Order 3 curve demonstrates the strongest trend.

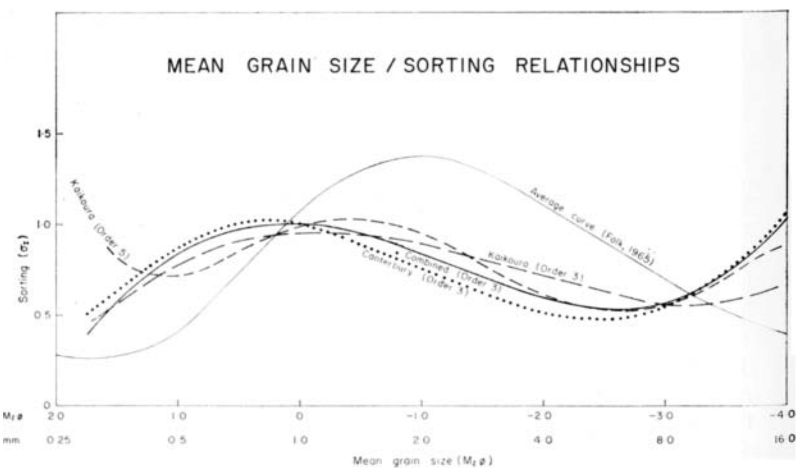

FIG. 5—Order 3 polynomial curves relating grain size and sorting for Kaikoura, Canterbury Bight, and combined data. The Order 5 curve for Kaikoura and the average curve from Folk (1965, p. 6) are also included.

TABLE 1—Results of Curve Fitting: Grain Size/Sorting

Data Set	Order of Polynomial	R (% Explanation)	F-level	Remarks*
Kaikoura	1	0·01	0·98	NS
	2	0·70	2·38	NS
	3	2·30	5·57	S
	4	5·80	0·12	NS
	5	5·80	4·95	S
	6	8·90	1·07	NS
Canterbury Bight	1	0·01	1·75	NS
	2	1·30	6·97	NS
	3	6·00	10·83	S
	4	12·70	0·82	NS
	5	13·20	4·44	NS
	6	15·90	3·15	NS
Combined	1	0·01	1·63	NS
	2	0·06	6·32	NS
	3	2·70	25·32	S
	4	10·40	3·17	NS
	5	11·30	6·04	NS
	6	13·20	3·51	NS

*NS—Not significant
S—Significant at 95% confidence level

Size/Slope Relationships

A scattergram relating observed grain size and foreshore slope values for the two beaches is shown in Fig. 6. As expected the general relationship reveals increasing slope angles with increasing particle dimensions. However, the relationship is not a simple one. From the distribution of values plotted, three additional features are apparent: (a) the scatter of slope values is not the same for all grain sizes; (b) lower slopes are not exclusively associated with the smaller materials; and (c) certain differences occur between the Canterbury Bight and Kaikoura values. These features will be considered in turn.

Firstly, a wider range of slope values is apparent in the granule and smaller pebble sizes than in materials either coarser or finer than these. Excluding the steepest slope for each size category, the slope range for granules and smaller pebbles ($-1·0\ \phi$ to $-2·5\ \phi$) is about 13°, while for coarser pebbles ($-2·5\ \phi$ to $-4·0\ \phi$) and sand grades ($< 1·0\ \phi$) is about 8° and 5° respectively.

Secondly, it is clear that slopes between 5° and 7° are found over the whole range of sediment sizes recorded. Thus, although the strong mode occurring between 4° and 7° on the slope frequency polygon (Fig. 3c (1))

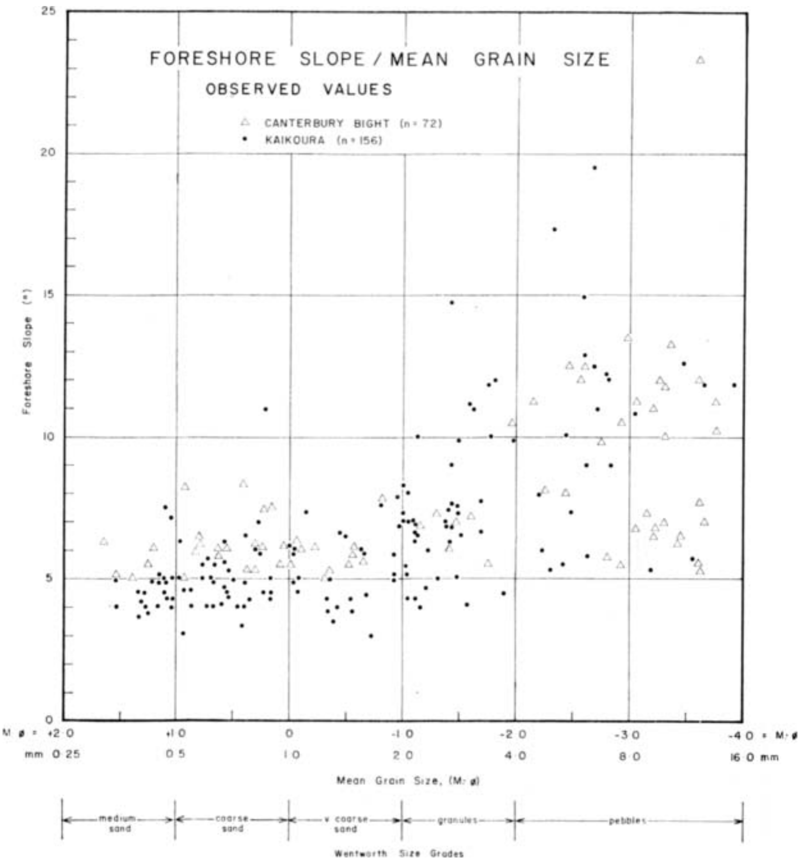

FIG. 6—Scattergram of observed mean grain size and foreshore slope values from Canterbury Bight and Kaikoura beaches.

is mainly associated with the sand sizes, it is evident from Fig. 6 that slopes developed on coarser materials also contribute to it. However, the converse is not true. With the exception of one isolated case, all surfaces steeper than 10° occur on materials coarser than $-1{\cdot}5\ \phi$ units, i.e., well above the sand sizes.

Thirdly, in view of the differences in average particle sizes on the two beaches (Fig. 3a) it is not surprising that differences are found in the values on the scattergram. In the sand-granule size grades, for example, the Kaikoura slopes are generally less steep than the Canterbury Bight slopes, while in the pebble fraction the ranges are about the same, but the Canterbury Bight pebble sizes cluster into two groups. Such differences, however, are minor and can be explained in terms of the inherent differences in the beaches themselves.

More significant is the nature of the size/slope relationship. Results of fitting polynomials of various orders to the data are shown in Table 2 and Fig. 7. These clearly indicate that for both beaches and for the combined data as well as the best fitting size/slope relationship is curvilinear. Table 2 shows that Order 3 curves appeared significant for the Canterbury Bight and combined data, but they were less significant than the Order 5 curves which in all cases provided the highest combinations of F-level tests and percentage of explanation of data variation. Order 5 curves have been plotted in Fig. 7 for the Kaikoura and combined data only. The print-out for the Canterbury Bight Order 5 curve was not available, but would be similar to the other two apart from having a lower amplitude. These curves reveal two peaks of rapid steepening of slopes in the medium sand and granule - fine pebbles sizes and two "plateaus" where slopes are constant, one in the coarse - very coarse sand sizes, the other in the coarser pebbles. It will be shown subsequently that such trends can be explained by reference to the trends in size/sorting of the materials.

While our concern here is with actual rather than average size/slope relationships for mixed sand-shingle beaches in two New Zealand areas, an average relationship compiled from data in Shepard (1963, table 9, p. 171) is plotted in Fig. 7 for comparative purposes. The data from which this curve was derived listed average beach-face slopes for various size grades from very fine sand through cobbles. Fig. 7 reveals two distinct differences between Shepard's and our data. Firstly, the shape of the curves are different. Presumably, the linear relationship displayed by Shepard's data results from considering "pure" types of beach sediment, whereas the mixed nature of beach materials investigated here result in the curvilinear trends. Secondly, apart from in the medium sand size grade, slopes from the Canterbury Bight and Kaikoura beaches are much gentler for equivalent particle diameters, i.e., they are sub-average. The Order 1 curve for the Canterbury Bight has been included in Fig. 7 to illustrate this difference. Included among the reasons for such low gradients are: (a) the greater variability in size-sorting on mixed beaches; and (b) the exposed nature of the east coast South Island beaches. It is worth recalling here that Wiegel (1964, p. 358) found that exposed beaches had lower beach-face gradients than protected beaches. Moreover, Kirk (in press) has argued with reference to the Canterbury Bight that lower gradients exist in this area because the beach is "under-nourished" and that as the shore is retrograding, beach profiles are becoming wider and flatter. The point here is that each beach will have its own characteristic foreshore slopes, which result from the interplay of controls, materials, and processes illustrated in Fig. 1.

Slope, Size, and Sorting Relationships

In the preceding discussion, *grain size versus sorting,* and *grain size versus slope* relationships have been described and analysed separately. Reference to the conceptual model (Fig. 1), however, shows that foreshore slope is a response not just to grain size, but also to size-sorting in the material factors. It is now argued that the characteristic foreshore slope/grain size patterns observed closely reflect the equally characteristic size/sorting patterns. Both the size/sorting and size/slope curves are curvilinear, the best fitting polynomials being of Order 3 and Order 5 respectively. By overlaying these curves, using grain size as the common axis, an indirect assessment of the interrelationships among the three variables can be made. Comparing Figs. 5 and 7 it can be seen that the two areas with the steepest gradients on the size/slope curves can be equated with the two areas of best sorting on the size/sorting curves, whilst the lower gradient modes are equated with the poorest sorting. More specially, reference to Fig. 5 shows that the two modes of poorest sorting for both beaches occur around $-0{\cdot}5\ \phi$ (very coarse sand) and $-3{\cdot}5\ \phi$ to $-4{\cdot}0\ \phi$ (coarse pebbles). These two modes are reflected in Fig. 7 by the "plateaus" of constant slope angles in the same size grades. Thus, it is suggested that poorer sorted materials will have lower slopes than well sorted materials of the same mean grain size, and conversely, that well sorted materials will provide steeper slopes than poorly sorted materials. In other words, had the very coarse sand and coarser pebbles on the Kaikoura and Canterbury Bight beaches had better sorting values, they would have had steeper slopes, and the resulting inflexions in the size/slope curves would have been much less noticeable.

TABLE 2—Results of Curve Fitting: Grain Size/Foreshore Slope

Data Set	Order of Polynomial	R (% Explanation)	F-level	Remarks*
Kaikoura	1	0·0	115·32	NS
	2	43·0	7·30	NS
	3	45·7	2·41	NS
	4	46·5	0·003	NS
	5	46·5	10·38	S
	6	50·0	4·75	NS
Canterbury Bight	1	0·1	21·62	NS
	2	23·7	0·00005	NS
	3	23·7	1·18	S
	4	25·0	0·03	NS
	5	25·0	1·39	S
	6	26·6	0·005	NS
Combined	1	0·1	126·5	NS
	2	36·1	1·90	NS
	3	36·6	3·38	S
	4	37·6	0·11	NS
	5	37·6	4·06	S
	6	38·7	0·49	NS

*NS—Not significant
S—Significant at 95% confidence level

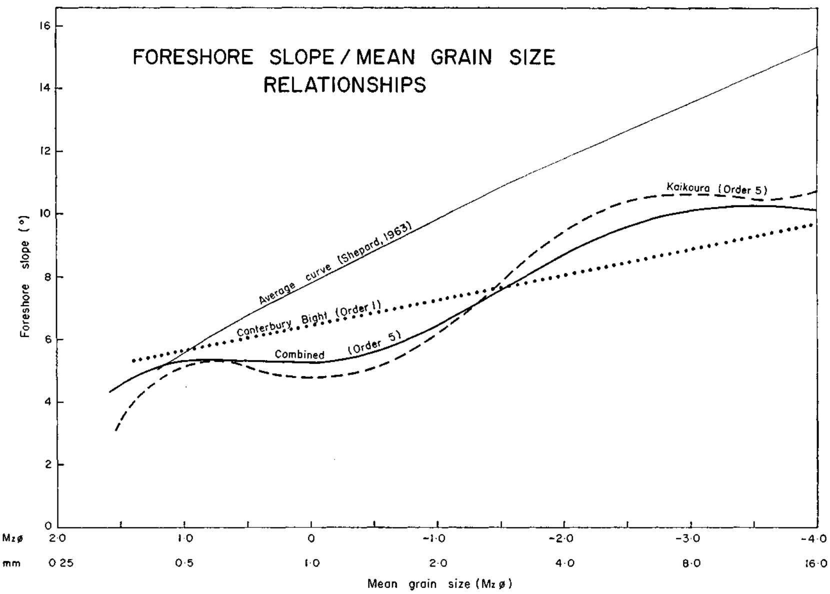

FIG. 7—Order 5 polynomial curves relating grain size and foreshore slope for Kaikoura and combined data. The Order 1 curve for Canterbury Bight and the average curve from Shepard (1963, table 9, p. 171) are also included.

It is apparent then, that where sorting improves over a range of grain sizes, it should be reflected in a steepening of the size/slope curves. Reference to Figs. 5 and 7 indicates that this indeed does happen on the Kaikoura and Canterbury Bight beaches, notably for grain sizes between $-1{\cdot}0\ \phi$ and $-2{\cdot}5\ \phi$. The size/sorting curves for both beaches have a negative slope in this region indicating better sorting from the granule to finer pebble sizes. This improvement in sorting is clearly reflected in the distinctive positive gradients in the size/slope curves giving a rapid increase in slope over the same size ranges.

The above data confirm the trend described by Krumbein and Graybill (1965, pp. 351–3) in a brief pilot study of size, sorting, and slope relationships of sand sized material. They found, for example, that well sorted coarse sand had a steeper slope than poorly sorted coarse sand.

Thus, it is possible to say for the mixed sand-shingle beaches investigated here that while grain size provides a primary control on foreshore slope sorting is also important in determining the actual slope. Moreover, the nature of the grain size/slope relationship closely reflects the nature of the grain size/sorting relationship, which in turn results mainly from the source area characteristics and secondarily from hydraulic factors. It should be noted, however, that it is via permeability that these material influences are transferred to foreshore slope.

CONCLUSIONS

Characteristic size/sorting and size/slope patterns for mixed sand-shingle beaches in two east coast, South Island areas have been described and analysed. The beaches have been shown to possess bimodal grain-size distributions which, though similar in form, differ in modal sizes. Significantly, in terms of the model presented, there is little difference in the gross sorting patterns of the beaches. Size/sorting relationships agree well with Folk's suggested "source area effect" in that size appears to be the primary control of sorting on the beach. On the other hand, hydraulic effects on the distribution of size/sorting values seem to contribute chiefly to variation in the spread of data. This is apparent from a comparison of the size/sorting trends in the Canterbury Bight data. Similar trends are suggested by both the foreshore and backshore samples, but the level of variability is much higher among samples gathered from the more frequently mixed and winnowed foreshore deposits on these high energy beaches.

The basic size/sorting trend is found to consist of two zones of good sorting occurring at $1{\cdot}5\ \phi$ to $2{\cdot}0\ \phi$ and $-2{\cdot}5\ \phi$ to $-3{\cdot}0\ \phi$ with sorting decreasing away from these regions. It has also been demonstrated that the distribution of foreshore slopes measured on the study beaches corresponds closely to the observed patterns of size and sorting. Thus, while there is a general relationship between mean size and foreshore slope, indicating increasing slope with mean grain diameter, in detail there are important deviations from the linear trend distinguished for smaller grain sizes by previous workers. This is of great significance in any consideration of the morphological forms of any given beach. The agreement demonstrated between the conceptual model and the field data confirms that, for mixed sand-shingle beaches at least, characteristic distributions of size and sorting will produce equally characteristic morphologic variations in a given beach deposit.

The size/slope curves for the study beaches have been shown to contain two "plateaus" of almost constant slope angles and two areas of almost linear increases in slope with size. The first are associated with the poorest sorted materials and the second with the best sorted materials. For mean grain sizes coarser than $-3{\cdot}0\ \phi$ the lack of a corresponding linear increase in slope probably also reflects the operation of other factors than those considered here. Chief amongst these are shape effects on the angle of repose of particles. The larger sizes on the study beaches tend to be predominantly discoidal in shape so that particle imbrication and orientation structures strongly influence the slope angle.

Though the hypothesis presented has been verified in a general manner, much more detailed analyses of size/sorting/slope relationships along and across the study beaches would be required, together with data on morphological responses to changes in wave energy, to develop the model any further. One weakness of the present technique of analysis is that each of the pairs of variables representing sedimentological and morphological responses has been considered separately. This has made for difficulty in estimating the precise degree of correspondence between paired variables. Because of this it is planned to repeat the analysis using trend-surface analysis in order to accurately and simultaneously locate the maxima and minima of correspondence between the three variables.

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