CHAPTER 25

WAVE PERIOD AND THE SWASH ZONE ENERGY BALANCE

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ABSTRACT

The shape sorting of pebbles in the swash zone was studied in an effort to determine the effect of the amount of foreshore infiltration per wave on the swash zone energy balance. Measurements were made of pebbles collected from the swash limit and from the step of selected sandy beaches. The pebbles were sampled on occasions when, and at locations where, the conditions of breaker height, breaker approach angle and foreshore slope fell within predetermined limits. The wave period and the foreshore infiltration rate varied among the beaches and were measured. The results of these measurements indicate that the mean shape of swash limit pebbles, and presumably, therefore, the swash zone energy balance depends upon the amount of foreshore infiltration per wave. This finding leads to the conclusion that in the study of the dynamics of the swash zone the effect of wave period and the effect of foreshore permeability must be considered together.

INTRODUCTION

The response of a beach to a particular set of sea conditions depends upon both its composition and its configuration. However, at the present time, the mechanics of beach processes are not sufficiently well understood to permit a quantitative prediction of the response of a given beach to a given set of conditions, despite the rapidly increasing need for such predictions. The following discussion is intended to contribute toward the eventual development of this predictive capacity.

Bagnold has discussed the ratio of backwash energy to swash energy as an important parameter in the study of the dynamics of the swash zone of beaches (Ref. 1). Backwash energy is less than swash energy by the amount of energy lost above a given potential level due to friction and infiltration into the foreshore. In the upper swash zone where velocities and turbulence are relatively low, the energy lost is mostly in the form of potential energy and depends primarily upon the amount of water which infiltrates the foreshore during the swash-backwash cycle. Thus Bagnold was able to demonstrate that foreshore slope, as a function of the energy ratio depends upon the permeability of the foreshore.

More recently, Kemp has reported on intensive studies of swash zone processes in which he emphasizes the role played by foreshore permeability in the control of wave energy absorption, beach slope, and the phase difference between swash duration and wave period (Ref. 2,3).

The purpose of the present paper is to report the results of field experiments which indicate that the amount of energy lost due to infiltration into the foreshore, and therefore the swash zone energy ratio, depends

upon both the foreshore permeability and the incident wave period. The experimental techniques make use of the readily observed movements and shape sorting of beach pebbles as external indices of the physically complicated swash zone mechanics. All of the studies and observations herein reported were made on the predominantly sandy beaches of Cape Cod, Massachusetts, which contain pebbles as a minor constituent (Fig. 1). The tides in the study area are semi-diurnal with mean annual ranges varying from 6.7 to 9.5 feet, depending on location.

BACKGROUND

It has often been reported that beach pebbles are sorted according to shape such that those deposited at the swash limit are flatter than those deposited at the step (Ref. 4). (As used in this paper, "swash limit" refers to the zone of deposition at the uppermost part of the swash zone, while "step" refers to the coarse deposit located at the final breaking point of the waves.) It has also been reported that swash limit pebbles are flatter on beaches of low permeability than on beaches of high permeability (Ref. 5). In addition, however, I have noticed over a number of years of field studies on Cape Cod beaches, that swash limit pebbles deposited under the action of short period storm waves are flatter than the swash limit pebbles deposited on the same beach when the wave period is longer. It occurred to me that the two effects may be due to the same cause. Both a decrease in permeability and a decrease in wave period act to increase the saturation of the foreshore and therefore decrease the amount of water which is lost from the swash due to infiltration into the foreshore. This suggested that the degree of flatness of swash limit pebbles is controlled by the ratio of the force exerted on the pebbles by the swash to the force exerted on the same pebbles by the backwash.

Preliminary field experiments designed to reveal the movements of beach pebbles provided information critical to the problem of pebble shape sorting (Ref. 6). In these experiments, painted pebbles were embedded in a chiefly sandy beach at 5-foot intervals and in a line normal to the shoreline between high tide and low tide lines. The pebbles were placed such that their top surfaces were visible, and the movements of each pebble were observed and recorded for 6-hour, half-tidal periods. The full results of these experiments will be published separately and this paper will include only those results immediately applicable to its subject.

The movements of the painted pebbles in the swash zone confirmed the existence of the continuous processes of erosion in the mid-swash zone and deposition in the upper swash zone and at the step as first described by Strahler (Ref. 7). Once exposed to wave action as a result of mid-swash zone erosion, the pebbles were moved by successive flows of the swash and the backwash until they were carried either to the step or the swash limit. Any pebble deposited at the swash limit had its immediate origin in the mid-swash erosion zone. No pebbles were carried directly from the step to the swash limit. If carried to the swash limit on the falling tide, the pebble was simply deposited there with no further movement. Although pebble shape was not considered during these experiments, later trials with matched pairs of similarly shaped pebbles clearly

demonstrated that the flatter the pebble, the more likely it was to be carried to the swash limit.

Another set of observations which bears upon the present discussion concerns the effect of pebble weight upon the shape sorting of beach pebbles. It was observed that when waves were large and steep, the sandy foreshore at low tide was commonly left "clean" with very few pebbles. Those which remained varied greatly in size, but all were extremely flat. On one such occasion, at Nauset Coast Guard Beach, an attempt was made to collect all foreshore pebbles large enough to be easily visible when walking for a distance of 350 feet. Eighteen pebbles were collected ranging in weight from 0.15 g. to 611.30 g. Despite the wide range of weight, the pebbles were all quite flat. Pebble shape was determined according to the coefficient $c/\sqrt{ab}$, where a, b, and c represent the lengths of the major, intermediate, and minor axes respectively. The values of the coefficient for the eighteen pebbles ranged from 0.09 to 0.37, even the largest of which describes a quite "flat" pebble.

PEBBLE SHAPE AS AN ENERGY RATIO INDEX

The observations of the movements of marked pebbles over half-tidal cycles indicated that the pebbles active in the swash zone on the falling tide have their immediate origin in the mid-swash erosion zone of the foreshore. These pebbles are in a condition of unstable equilibrium because the ratio of the force exerted by the backwash to the force exerted by the swash decreases going up the foreshore. Once exposed to the alternate action of the swash and backwash, they are eventually deposited either at the step or at the swash limit. If a pebble, such as a very flat pebble, is moved by the swash but not the backwash, it is deposited at the swash limit. If another, say a nearly spherical pebble, is easily moved by both the swash and the backwash, it is deposited at the step due to the downslope component of gravity. If, however, there were no backwash, that is to say, the ratio of the force exerted by the backwash to the force exerted by the swash equaled zero, even a sphere would be deposited at the swash limit; and if the ratio equaled one, even the flattest pebble would be taken to the step. Since the forces exerted on pebbles are proportional to the kinetic energies of the flows, and since the sorting action is considered to take place at a single potential level, the mean shapes of the pebbles which are left scattered on the foreshore by the falling tide were taken as an index of the ratios of the backwash energy to the swash energy which existed in the mid-swash zone at the time of their deposition.

DESIGN OF FIELD EXPERIMENTS

In the field experiments to be described, the intermediate axes of the pebbles sampled ranged from 0.5 inches to 2.0 inches. Pebbles of this size were found to be readily movable by the swash of the beaches selected. It was assumed that the pebbles would be sorted according to their shape independent of their weight. This assumption was confirmed by the analysis of the data.

The experiments were performed at mid-tide on the falling tide on beaches which were selected such that the foreshore slopes were $7^{\circ} \pm 30'$,

the breaker heights were 1.5 feet $\pm$ 0.5 feet, and the breaker approach angles were $0^{o} \pm 10^{o}$. This permitted the assumption that the value of the swash energy was constant in all experiments, and therefore that the value of the energy ratio in the mid-swash zone depended only upon the energy lost, in the form of potential energy, due to infiltration into the foreshore in the upper swash zone. It was further assumed that the volume of water which infiltrated the upper foreshore per wave was a function of the foreshore infiltration rate, Q , ($cm^3/ cm^2/ sec$), and the incident wave period, T , (sec). The product, QT , will be referred to as the "infiltration-per-wave" index. QT has the dimensions of length, and it may be thought of either as an index of the volume of water which infiltrates a unit area of foreshore per wave or as an index of the vertical displacement of the foreshore water table between successive swashes.

In brief, the field experiments to be described were designed to test the hypothesis that on beaches of a given slope, acted upon by breakers of a given height and approach angle, the energy balance of the swash zone, as indicated by the mean shape of the pebbles deposited at the swash limit on the falling tide, is a function of both the foreshore infiltration rate and the incident wave period, as indicated by the infiltration-per-wave index.

EXPERIMENTAL PROCEDURE

On a given day a site was sought within the study area where breaker height, breaker approach angle and foreshore slope all fell within the given limits. Breaker height and approach angle were estimated visually. Foreshore slope was determined by means of an inclinometer (Brunton compass) resting on a timber. The $7^{o} \pm 30'$ limits were chosen because foreshore slopes in the study area were frequently within that range and because experience indicated that this was sufficiently steep to produce backwash accelerations such that pebbles were moved before the commencement of scour which, as has been reported by Johnson (Ref. 8) and Smith (Ref. 9), can lead to burial. It was also required that the wave form be simple, that is, that practically speaking, only a single wave train be running. Finally, it was required that variations along the shore at the site be minimal. If these basic requirements were satisfied, and pebbles were in evidence, an experiment was conducted. Each experiment was designed so that the foreshore pebbles sampled were those which had been deposited at approximately mid-tide on the falling tide in order to minimize the variations in the relative position of the beach water table due to the propagation of the tidal wave through the beach (Ref.10).

Each experiment began shortly before mid-tide. First, general wave and beach characteristics were noted, and then a determination of wave period was made by measuring with a stop watch the time interval between breakers. This done, iron rods were placed along shore at the swash limit marking the top of the foreshore area to be sampled. The length of the sample area varied with the pebble concentration from a minimum of 27 feet to a maximum of 300 feet. After placing the top foreshore sample area boundary rods, the step pebbles were sampled with a fine mesh dip net

from a position seaward of the step and along the entire length of the step seaward of the foreshore sample area. Brought back to the dry beach, the step pebbles were size-sorted using an aluminum template with hole 0.5 inches and 2 inches in diameter. Only those pebbles were retained which would pass through the larger hole but not the smaller one. The others, with an intermediate (b) axis less than 0.5 inches or greater than 2 inches were discarded. This method of size-sorting, which was used for both the step and foreshore pebble collections, was the source of a sampling error which was later detected and corrected, as is later discussed in this section. The step pebble collection was completed when 100 pebbles had been gathered.

Sampling Foreshore Pebbles

When the tide had dropped far enough, the iron rods marking the bottom of the foreshore sample area were placed at the swash limit in a line along shore, downslope from the top rods. On the foreshore sample area, between the two rows of rods lay the pebbles which had been deposited at the swash limit while the step pebbles were being sampled. The foreshore sample area was always narrow (9 to 15 feet in width) as compared to its length, because foreshore variations are generally more extreme up and downshore than along shore. After the setting of the bottom foreshore sample area rods, the wave characteristics were determined again in the same manner as before, thus giving a reading at both the beginning and the end of the period during which the sample pebbles were deposited. All of the collections and measurements which then remained to be made concerned the rectangular foreshore sample area. In most of the experiments this area measured 9 feet by 27 feet, and a method was devised to take a random sample of approximately 100 pebbles from within the area. If, however, the foreshore pebble concentration was such that there were fewer than 100 pebbles within the standard 9- by 27-foot area, the sample area was increased so that it contained approximately 100 pebbles, and in such cases all pebbles (0.5 inches $< b <$ 2 inches) within the area were taken for the foreshore sample. A maximum permissable size for the foreshore sample area was set at 15 feet by 300 feet. If it so happened, as it did once, that there were fewer than 100 pebbles in an area of this size, the foreshore pebble sample consisted of the total number of proper sized pebbles found within the area, regardless of how few they might be. This limit was set because it was felt that the variations inherent within an area larger than this would necessarily be too great to justify the assumption that the mean value of the variables measured within the sample area were characteristic of the entire area.

The following describes the methods of sampling within the 9- by 27-foot areas. Adaptations of the sampling techniques necessary for the larger areas will be self-evident. The 9- by 27-foot rectangle was divided into three 9-foot squares, the corner of each square being marked by an iron rod. The center of each square was marked by an upside-down sample bucket. These would later be the locations for the three samples to be taken for the determination of the foreshore infiltration rate. At two locations halfway between buckets, the foreshore slope was determined by the methods previously described. Next, the foreshore pebbles were collected. For this purpose each square was visually divided into quadrants. If there were less than about 14 pebbles of the proper size per quadrant, all pebbles in the 12 quadrants were collected after

being checked for size, using the template previously described. If there were more than about 14 pebbles per quadrant, use was made of one of four aluminum hoops which had diameters of 3, 2, 1.5 feet and 1 foot. The hoop was chosen which would encircle approximately 5 to 10 pebbles of the proper size. This hoop was then tossed successively in each of the 12 quadrants, and all pebbles encircled, after being checked for size, were kept.

Infiltration Rate Determination

The infiltration rate of the foreshore sand was determined by a system basically similar to one described by Emery and Foster (Ref. 10). The core tube made of lucite plastic was 6.58 cm. in diameter and 50 cm. in length. The cores were taken by inserting the tube vertically into the sand at the three locations previously described within the foreshore sample area. The length of each core was kept constant at 15 cm. Disturbance to the core in sampling was minimized by digging a moat of depth equal to the core length around the region to be sampled, leaving a sand column with a diameter only slightly larger than that of the core tube. After the core tube had been inserted to a depth of 15 cm., a thin aluminum plate was slid across the bottom of the tube,thus preventing core disturbance in removal. Once removed, the plate and upright core tube were placed upon a square of cloth resting on a board. The aluminum plate was then carefully slid out and the cloth pulled up and around the tube and secured in place with a stainless steel hose clamp. The core was then slowly immersed in a tall bucket of sea water taken only a short while previously in order to minimize temperature change and thus to take into account the local temperature effect on viscosity. It was found that if a pressure head of about 3 cm. was maintained during the saturation of the core, there was virtually no disturbance to the sample. The water level was allowed to continue rising in the core tube until it stood somewhat above a mark 30 cm. from the bottom (and 15 cm. above the top of the sample). The tube was then capped at the bottom and taken to a nearby stand to which it was attached in a position below a reservoir containing one liter of sea water. The cap was then removed and when the water level within the tube fell to the 30 cm. mark, water was allowed to flow into the core tube from the reservoir. At this instant a stop watch was started. During the entire test the water was kept at the 30 cm. mark. When the reservoir was exhausted, the stop watch was stopped. In this manner, a measurement was made of the time required for one liter of sea water with a head of 30 cm. to flow through a 15 cm. length of relatively undisturbed beach sand with a known surface area. This test was made three times during the experiment and the results averaged to give a measurement of the infiltration rate per unit area of local sea water through the sand of the foreshore sample area.

Laboratory Analyses

Ten such experiments were performed, not including two preliminary experiments which were performed prior to the initiation of the standardized procedure. The pebble samples were analyzed in the laboratory. First, each pebble was weighed: to the nearest gram for five samples and to the nearest 0.1 gram for the others. Next, a determination was

made of the lengths of the major axis, "a", the intermediate axis, "b", and the minor axis, "c". Specifically, "c" was taken as the vertical extent of the pebble above a horizontal plane when the pebble lay in its preferred stable position. Axis "a" was assumed to be the greatest dimension of the pebble in a plane perpendicular to "c", while axis "b" was the maximum distance covered by the pebble in a direction perpendicular to both "a" and "c". The axial lengths were each measured to the nearest millimeter: the "a" and "b" axes by laying the pebble in the corner of a specially designed box having orthogonal graph paper graduated in millimeters affixed to the surface of the bottom. The "c" axis was measured by means of vernier calipers.

Following the axial measurements, the shape of each pebble was determined by calculating the value of the coefficient $c/\sqrt{ab}$. It was then noted that there was a certain correlation between pebble weight and pebble shape in the respect that for each sample the pebbles which weighed less than 3 grams had a mean $c/\sqrt{ab}$ value which was lower than that of the remainder of the sample. This correlation was discovered to be a fallacious one — the result of a bias introduced by the sampling method. By rejecting all pebbles with a "b" axis length less than 0.5 inches, the lightest weight classes were in fact "enriched" with flatter pebbles. Similarly, the rejection of all pebbles with a "b" axis length greater than 2 inches would tend to decrease the percentage of flat pebbles in the highest weight classes. However, as is commonly the case of pebbles in all natural environments, the sampled pebbles were approximately log normally distributed by number with respect to weight. Light pebbles were much more numerous than heavy ones, and therefore the bias did not show up in the heavier weight classes.

An analysis of the distribution of pebble shapes within the samples revealed that the heaviest pebble likely to pass through the 0.5 inch hole would weigh less than 3 grams, while the lightest pebble likely to be too large for the 2 inch hole would weigh more than 80 grams. Therefore, all pebbles which weighed less than 3 grams or more than 80 grams were rejected. This left a total of 1,609 pebbles in the twenty samples. Plots of pebble shape frequency within randomly selected samples on normal probability paper indicated that the pebbles in each sample were normally distributed with respect to shape.

The sample statistics, sample mean and standard deviation, were computed by means of a General Electric 225 computer making use of the preliminary portion of a factor analysis program written and published by Derek W. Spencer (Ref. 11). This program also permitted the computation of various transforms of the original variables (a, b, c, and weight) for each pebble. Finally, a correlation matrix was provided of the original and transformed variables for each sample.

RESULTS

The results of the field and laboratory measurements are summarized in Table 1. Column 1 gives an abbreviation of the name of the beach from which the samples were taken (Fig. 1) and a notation of the zone

sampled: foreshore (F) and step (S). Column 2 gives the mean shape, $\overline{c/\sqrt{ab}}$, of the pebbles in each sample; column 3 the standard deviation, σ, of the distribution; and column 4 the number of individuals, n, in each sample. Column 5 records the mean value of the infiltration rate, Q, measured at each foreshore sample area. Column 6 gives the mean value of the wave period, T, measured at the time the samples were taken. Column 7 shows the value of the infiltration-per-wave index, QT, calculated for each site. It is the product of the values in columns 5 and 6. Column 8 gives $(QT)^{-1}$, the inverse of the values in column 7, and column 9 shows the symbol used to represent each sample location on Figure 2.

Foreshore Pebble Samples

In Figure 2 the x's and dots represent the values of the mean shapes of the foreshore pebble samples, $\overline{c/\sqrt{ab}}$, plotted against the mean values of the corresponding infiltration-per-wave index, QT. The dots represent the results of two preliminary experiments as explained in the footnote to Table 1. Seeking a transformation which would produce a linear relationship between $\overline{c/\sqrt{ab}}$ and some function of QT, it was found that a suitable transformation was $(QT)^{-1}$, the values of which are given in column 8 of Table 1. The least square regression line of $\overline{c/\sqrt{ab}}$ on $(QT)^{-1}$ was found to be:

$$\overline{c/\sqrt{ab}} = -0.55\ (QT)^{-1} + 0.66. \qquad (1)$$

The correlation coefficient between the two sets of variables was found to be -0.92. The 95 per cent confidence limits for the correlation coefficient are -0.69 and -0.99. The standard error of estimate of $c/\sqrt{ab}$ on $(QT)^{-1}$ is 0.046. The standard error of the regression coefficient was found to be 0.08. The 95 per cent confidence limits of the regression coefficient are -0.55 ± 0.19, and the 99 per cent confidence limits of the regression coefficient are -0.55 ± 0.28.

Making use of Student's "t" test to test the hypothesis that the regression coefficient is equal to 0 at a significance level of 0.01, we find that we must reject the hypothesis. That is to say, at the 0.01 level of significance, the shape of the foreshore pebbles is a function of the infiltration-per-wave index.

The least square regression line of $\overline{c/\sqrt{ab}}$ for foreshore pebbles on Q^{-1} alone was found to be:

$$\overline{c/\sqrt{ab}} = -0.052\ Q^{-1} + 0.56. \qquad (2)$$

The correlation coefficient between the variables is -0.77, while the standard error of estimate of $\overline{c/\sqrt{ab}}$ on Q^{-1} is 0.076. A comparison of these statistics with the corresponding statistics for the regression line of $\overline{c/\sqrt{ab}}$ on $(QT)^{-1}$ indicates the importance of the incident wave period, T, in the regression of $\overline{c/\sqrt{ab}}$ of the foreshore pebbles.

The lower solid line in Figure 2 shows the regression equation, rewritten in terms of QT, plotted on the scatter diagram of the data points. This equation has the form:

$$QT(0.66 - \overline{c/\sqrt{ab}}) = 0.55. \qquad (3)$$

TABLE 1

REDUCED DATA FROM FIELD EXPERIMENTS

1 Location		2 $c/\sqrt{ab}$	3 σ	4 n	5 Q cm/sec	6 T sec	7 QT cm	8 $(QT)^{-1}_{cm^{-1}}$	9 Symbol
RP	F	0.60	0.12	93	1.00	5.0	5.0	0.20	x
	S	0.54	0.13	95					+
HM	F	0.49	0.13	73	0.69	7.0	4.8	0.21	x
	S	0.58	0.12	88					+
GH	F	0.46	0.15	70	0.86	4.5	3.9	0.26	x
	S	0.65	0.12	97					+
FB	F	0.46	0.13	76	0.81	4.3	3.5	0.29	x
	S	0.59	0.14	93					+
HH	F	0.56	0.13	86	0.85	3.8	3.2	0.31	x
	S	0.58	0.14	93					+
P3	F	0.45	0.13	61	0.32	9.2	2.9	0.34	x
	S	0.58	0.12	89					+
HC	F	0.48	0.14	84	0.82	3.3	2.7	0.37	x
	S	0.59	0.13	89					+
BP	F	0.45	0.13	71	1.14	2.3	2.6	0.38	x
	S	0.52	0.17	89					+
P2	F	0.40	0.14	79	0.20	10.6	2.1	0.48	x
	S	0.51	0.12	88					+
N3	F	0.18	0.03	2	0.20	6.0	1.2	0.83	x
	S	0.54	0.15	93					+
N2*	F	0.27	0.11	13	0.17	10.0	1.7	0.59	●
	S	0.67	0.12	14					◆
N1*	F	0.22	0.08	18	0.16	6.0	1.0	1.00	●
	S	0.55	0.14	14					◆

*The beaches N1 and N2 were sampled prior to the initiation of a standardized procedure. Beach slope varied considerably from the experimental $7^{\circ} \pm 30'$ and the values for the wave period were obtained from another source. The data from N1 and N2 are not included in the following calculations and are presented only for the sake of completeness.

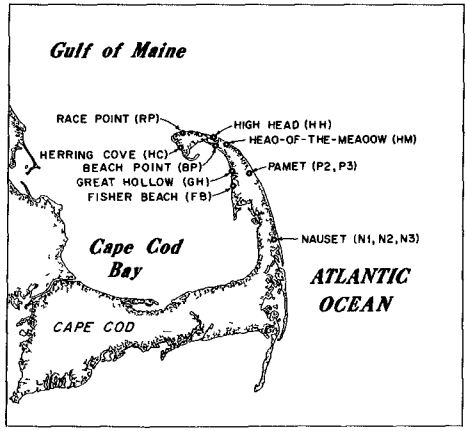

Fig. 1. Location of field experiment sites on Cape Cod, Massachusetts.

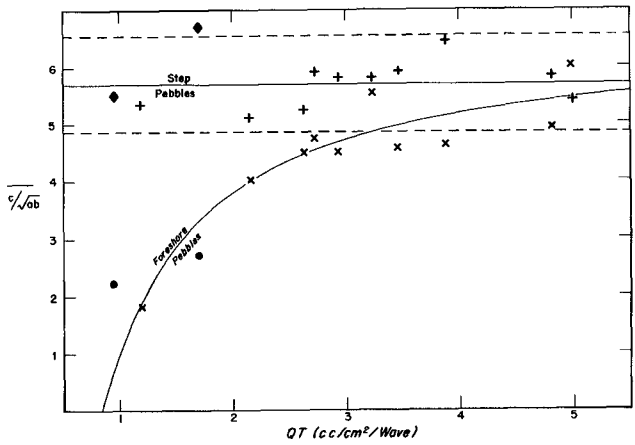

Fig. 2. Distributions of mean shapes of foreshore and step pebble samples with respect to mean values of infiltration-per-wave index of foreshore at time of sampling. Upper solid line and two dashed lines represent the mean of means and 95% confidence interval of means of step pebble samples. Lower solid line is least square regression line of best fit for foreshore pebble samples. Symbols explained in Table 1.

Step Pebble Samples

In Figure 2 the crosses and diamonds represent the values of the mean shapes of the step pebble samples, $\overline{c/\sqrt{ab}}$, plotted against the mean values of the corresponding infiltration-per-wave index, QT . The least square regression line of $\overline{c/\sqrt{ab}}$ on QT was found to be:

$$\overline{c/\sqrt{ab}} = 0.014\ QT + 0.52. \quad (4)$$

The correlation coefficient between the two sets of variables is 0.46, while the 95 per cent confidence limits for the correlation coefficient are -0.23 and 0.82. The standard error of the regression coefficient was found to be 0.011. The 95 per cent confidence limits of the regression coefficient are 0.014 ± 0.024, and the 99 per cent confidence limits of the regression coefficient are 0.014 ± 0.036. An application of Student's "t" test indicates that we cannot reject the hypothesis that the regression coefficient is equal to 0 at the 0.01 significance level.

Due to the lack of a significant correlation between the mean shapes of the step pebble samples and the values of the infiltration-per-wave index, the upper solid line of Figure 2 represents the mean shape of the total step pebble population, which is given by the mean of the means of the individual step pebble samples:

$$\overline{\overline{c/\sqrt{ab}}} = 0.57. \quad (5)$$

The dashed lines indicate the 95 per cent confidence interval of the step pebble means. Since the lower solid line represents the best estimate of the variation of the mean shape of the foreshore pebbles with respect to the beach infiltration-per-wave index, the figure indicates that the degree of shape sorting of pebbles on the foreshore of the sampled sandy, tidal beaches is dependent upon the period of the waves and the infiltration rate of the foreshore as expressed by the infiltration-per-wave index.

DISCUSSION

Table 2 gives the values of the correlation coefficients (r) calculated between pebble weight and pebble shape ($c/\sqrt{ab}$) for each of the twenty samples used in the foregoing analysis. The size of each sample (n) is also indicated. The low values of the correlation coefficients indicate that there is no relationship between the shape and the weight of the step pebbles. This is to be expected since the step pebbles represent the total, non-sorted pebble population. The correlation coefficients for the foreshore pebbles are also low (except for N3 which, since it consists of only two individuals, must give a value of 1.000). An application of Student's "t" test indicates that at the 5 per cent significance level the hypothesis that the population correlation coefficient is equal to zero, for any of the populations from which these samples were selected, cannot be rejected. On the other hand, the fact that the correlation is negative in every case suggests that in fact there is a slight decrease in the value of the shape factor with an increase in weight. However, since even in the case of the highest correlation, FB foreshore, the variation of the weight

explains less than 5 percent of total variation in shape, the relationship between the infiltration-per-wave index and the mean shape of the foreshore pebbles would not be appreciably affected by any variation in the proportion of pebble weights which might have occurred between the samples.

TABLE 2

COEFFICIENTS OF CORRELATION BETWEEN PEBBLE WEIGHT AND PEBBLE SHAPE

Sample		r	n	Sample		r	n
BP	F	-0.080	71	GH	F	-0.202	70
	S	0.232	89		S	0.282	97
HH	F	-0.001	86	HM	F	-0.186	73
	S	-0.051	93		S	-0.001	88
HC	F	-0.162	84	RP	F	-0.075	93
	S	-0.032	89		S	0.213	95
P2	F	-0.164	79	FB	F	-0.223	76
	S	0.019	88		S	0.117	93
N3	F	-1.000	2	P3	F	-0.152	61
	S	-0.012	93		S	-0.089	89

The shape of foreshore pebbles and therefore the ratio of backwash energy to swash energy, both dimensionless quantities, have been related to the inverse of the infiltration-per-wave index which has the dimension (L^{-1}) with the result that the constant, 0.55, of equations (1) and (3) must have the dimension (L). Recalling that the experiments were performed on beaches chosen with constant values for breaker height, breaker approach angle,and foreshore slope, let us now generalize this concept and consider the dynamics of the swash zone to depend upon the ratio of infiltration rate of water into the foreshore to the rate of supply of water by breakers. Consider: the infiltration rate to be proportional to the infiltration rate per unit area, Q , times the foreshore swash area; the foreshore swash area per unit length of shoreline to be given by the distance of the swash run-up; the swash run-up to be proportional to $H/\sin\theta$, where H is the breaker height and θ is forshore slope; and the breaker angle to reduce the expression by the amount, $\cos\phi$, where ϕ is the angle between the breaker crest and the shoreline. Thus:

$$\text{infiltration rate} \sim Q(H/\sin\theta)\cos\phi. \tag{6}$$

Assuming that the breaker volume per unit distance of shoreline is proportional to H^2 and again multiplying by $\cos\phi$ to account for breaker angle:

$$\text{supply rate} \sim H^2\cos\phi/T. \tag{7}$$

Dividing (6) by (7) and simplifying yields:

$$\frac{\text{infiltration rate}}{\text{supply rate}} \sim \frac{QT}{H\sin\theta} \tag{8}$$

It is interesting to note that the breaker angle, ϕ , does not appear in the final expression.

Such a ratio may be thought of as a coefficient of similarity for the swash zone, and variations in its value could possibly be related to

variations in beach stability. By maintaining constant values of H and Θ, and by making an estimate of Q from infiltrameter measurements, the results of the study of shape sorting of foreshore pebbles yield partial support for the validity of this coefficient. This is not to underestimate the gross simplifications implied by the above formulation, in particular, the difficulties of obtaining an accurate measure of Q and the unlikelihood in nature of constant values for T, H, and Θ; rather it is to suggest a possible relationship between some of the more important factors involved in the dynamics of the swash zone of beaches.

SUMMARY

Field experiments performed on predominantly sandy, tidal beaches indicate that the mean shape of the pebbles deposited on the foreshore during the falling tide depends upon both the foreshore infiltration rate and the incident wave period. If the mean shape of the foreshore pebbles is taken as an index of the ratio of the backwash energy to the swash energy, the results suggest that in the study of swash zone mechanics the amount of foreshore infiltration per wave be considered rather than the rate of foreshore infiltration alone.

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