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A Field Investigation Study to Determine the Properties of Windblown Beach Sand

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ABSTRACT

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A field investigation was carried out on the prototype beach to determine the properties of windblown sand and parameters governing the aerial transport. The results suggest that the sand separates into two strata but the dynamics involved in this stratification process are still uncertain.

ADDITIONAL INDEX WORDS: *Coastal dunes, coastal erosion, sediment transport, erosion processes.*

INTRODUCTION

The phenomenon of windblown beach sand has always been of interest to coastal engineers. The mechanics are complex and often very site-specific in terms of beach exposure, wind climate and type of sand. This study records one example of data on the process as collected on the prototype. It is found that the distribution of windblown particles is different from those as determined in wind tunnels (*e.g.,* BAGNOL {1942}) and apparently also different from those as detected in the inland desert regions. The main reason for the latter appears to be the resulting age of the parent sand materials and the constraints induced by the limitations of the size of the tunnel.

On the Gold Coast of Queensland, a great deal of effort has been expended over the years in stabilising the local beach dunes with sand drift fences and colonising them with natural vegetation. This effort has been concentrated upon addressing the results of natural wind-blow and practically no research has been conducted to date upon the mechanics of the local windblown transport itself. In fact, only one exercise to measure the properties of the windblown material itself has ever been conducted to date, and this paper records the results of that exercise.

Sampling Procedures

The airborne sample was recovered on a strip of 50 mm sticky plastic tape attached vertically to a heavy striking hammer handle. The tape was exposed for 120 seconds near the centre of the aerial beach under a steady breeze running at 5.6 m/sec when measured at a height of 1,500 mm above ground level. The beach surface was smooth and ripple-free with a slope towards the ocean of some 1 in 10. The wind was onshore and slightly oblique to the beach. The tape was observed continuously and all the travelling sand particles appeared to have been captured, since none were seen to bounce off the tape. The tape surface was aligned normal to the wind.

The beach surface and sub-surface (parent) samples were recovered by pressing a circular plastic straight sided container into the beach until it was completely full. To prepare the surface mini-armour sample, the "top" of the container was cut off with a fret saw and a piece of the same sticky tape was pressed onto the original sand surface. The parent sample was then recovered from the remaining total body of sand in the container, by progressive splitting through a microsplitter, multi-repeated rolling on textured paper and finally picked up on a sugar coated glass slide using the procedures of SMITH and GORDON (1980, 1982).

In the laboratory, the airborne sample plastic sticky tape was trimmed off above the highest adherent sand grain and marked off into seven equal sections 50 mm wide and 43 mm high.

Sample Parameters

The vocabulary normally used to describe sediment can at times become ambiguous and rather confusing. For example, the adjective "large" may be used to describe a grain which has a high mass, long width, or low specific surface, when in fact each of these parameters are quite different. To prevent any ambiguity, we will spell out the following definitions as applicable in this paper.

The terms "light" and "heavy" will describe particle mass, "large" and "small" will describe only the particle width, and "fine" and "coarse" will describe only specific surface.

It was not feasible to sieve test the various sand fractions because the weight of each sample was so small and in addition the individual grains held a significant volume of "stick" gained from their contact with the tape. Instead it was decided to scan the samples under an 80× microscope and determine each particle populations' specific surface and par-

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Table 1. *Sand population data.*

Sample	Height (mm)	Particle Count (N = grains/gram)	Weight Density Grams/mm^2 $\times 10^{4}$
Parent	Below surface	13,760	38.10*
Mini-armour	Surface	4,200	8.88*
1	20	29,760	5.90
2	60	51,230	3.61
3	100	60,340	2.59
4	140	37,500	2.92
5	180	46,430	0.82
6	210	39,450	0.65
7	245	51,800	0.38

Table 2. *Sand population densities.*

Sample	Below Surface	Particle Density (grains/mm^2)	Rate Of Transport (Q = grains/mm^2 sec)
Parent	Below surface	17.0*	—
Mini-armour	Surface	2.8*	—
1	20	17.6	0.146
2	60	18.5	0.154
3	100	15.6	0.130
4	140	10.9	0.092
5	180	3.8	0.032
6	210	2.6	0.021
7	245	1.9	0.016

ticle count using the techniques of SMITH (1992). Within each marked section of the "airborne" tape, the "mini-armour" tape and the "parent" slide, a minimum number of 70 grains, being every grain within a given area, were scanned through a collimation grid under side lighting. Since no heavy mineral grains were found on any of the scans, a constant S.G. = 2.65 was applied to all the grain calculations, the particle populations consisting almost entirely of shell and silica grains.

It remains however, that the parameters of specific surface, and particle count, *i.e.,* the number of grains per gram, are very seldom applied to the study of beach sand behaviour, either in water or in air, but instead the parameter of sieve D50 size is almost universally applied and adopted. Accordingly it was deemed essential to assess this parameter, as well, even though the use of "sticky tape" and the small number of adherent grains caught thereon, precluded standard sieve testing. Fortunately, in the event, this was possible, because the microscopic scans detected each of the three principal dimensions of each grain. From the particle scan data then, it was possible to use the second dimension "b" as a surrogate for the equivalent sieve "diameter size", see SMITH (1992). The basic data recovered is set out in Table 1.

The height intervals between the airborne sample scans are not constant because near the top of the tape there were not enough grains available to make up the minimum population sample number. The top 500 sq. mm of tape for example held only 27 grains. The particle population densities were also measured and these are set out in Table 2.

The values in Table 2 marked with an asterisk are not at all comparable with the remainder of the tabulated values, because in these the sample preparation determined the results, not the sorting processes of the wind.

Specific Surface

The specific surface determinations all provided a reasonable fit to the log-normal distribution and the resulting plots are shown in Figure 1. In making the microscopic scans the dominant feature of the airborne sand populations was that the grains were almost universally embedded on the tape "end-on". The particles were aligned with their two largest "sides" parallel with the ground and they were held onto the tape by their smallest "surface". This observation was somewhat unexpected—bouncing and saltating grains might be more likely to be tumbling around their own axes but it appears that this is not generally so. It seems therefore that the wind's surface drag must readily position airborne particles into a minimum drag alignment, very rapidly. What is here surprising perhaps is that the wind velocity, *i.e.,* 20 km/hr, was quite modest.

The specific surface plots of Figure 1 then show some further irregular behaviour. The mini-armour population as would be expected, has a lower F50 than the buried parent population, *i.e.,* it is much coarser yet the two plots are parallel. The parent population is also significantly coarser than all the airborne populations but only sample 4 has a plot parallel to the parent and mini-armour samples. The plots of samples 1, 3, 5, 6 and 7 are generally parallel within themselves, but their plot slope is much flatter and sample 2 is completely anomalous. Smith (1992) detected that the specific surface plots of all seabed beach sands on the Gold Coast (and some in N.S.W.) were universally sensibly parallel—in fact quite parallel with the mini-armour, parent and sample 4 plots of Figure 1. It must be reasonable to conclude therefore that the selective transport of beach sand by the wind is rather different from the transport of sand by waves and currents, *i.e.,* the natural sorting does not follow the same laws in detail. This would be very reasonable, the densities of air and water are Poles apart, as are their relative velocity "inputs" into beach sediments.

Figure 2 then shows the plot of the sample F50 specific surface against height. The plot generates two separate groups of points with a complete trend "break" at a height of 100 to 120 mm. It is not easy to explain this apparent jump in properties, but as shown on the figure, it might be reasonable to deduce that the bottom three points demonstrate what might be called "Bedload Transport", whilst the upper four points represent "Flying Transport". This might offer some explanation for the anomalous slope of the plot of sample 2 in Figure 1.

GOLDSMITH (1985) states that during saltation, large sand grains will generally bounce higher than small grains, creating a zone of fine (High F value) particles. Later in this paper, however, we will suggest that the shape of the sand grains could be another important factor.

A similar trend is then shown in Figure 3 which gives a "density" plot of populations in trapped grains/sq. cm against height. Again a discontinuity appears near the 120 mm

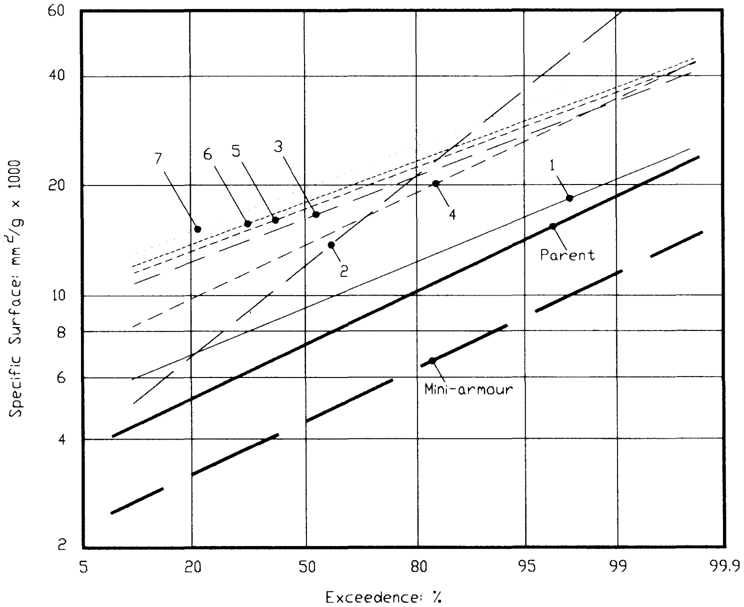

Figure 1. Beach sediment properties.

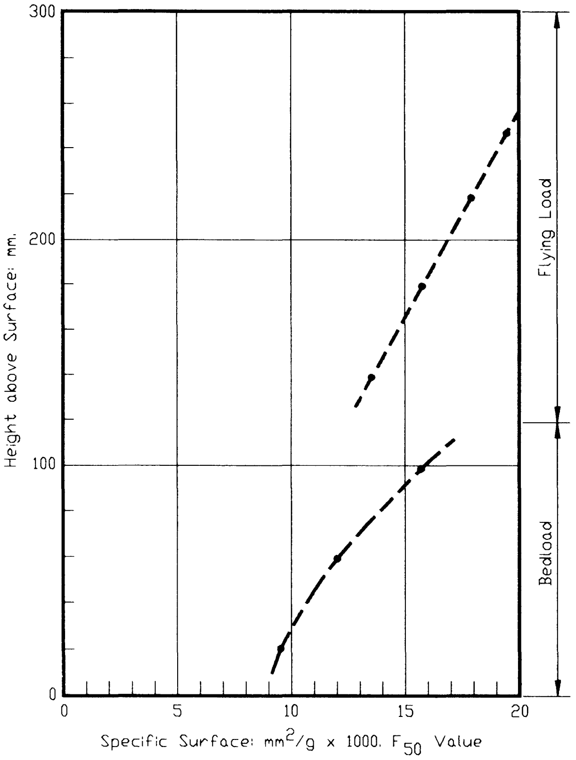

Figure 2. Relationship between height of sample and F value.

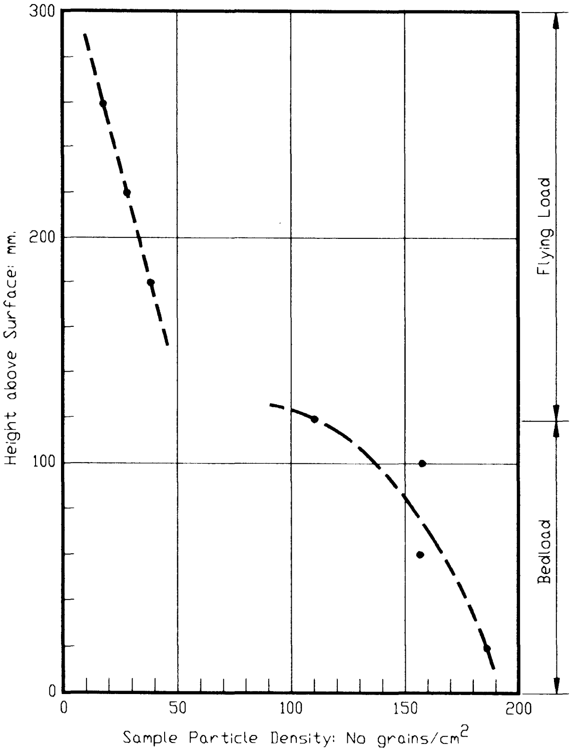

Figure 3. Relationship between grain density and height.

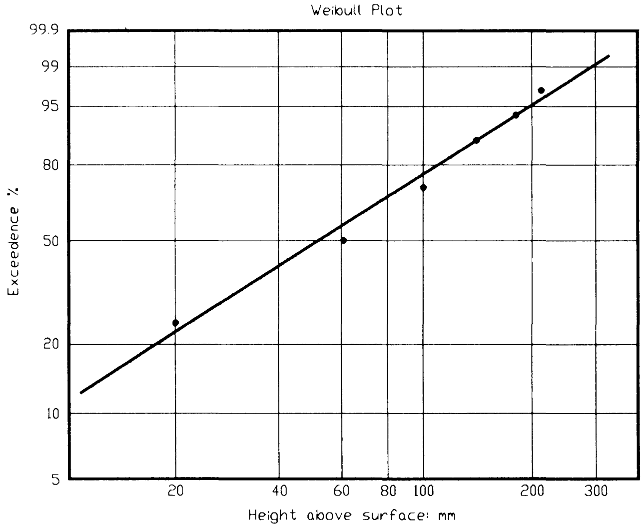

Figure 4. Relationship between total volume of transport and height.

height but sample 4 here seems to fit the lower group, rather than the upper.

A different look at particle density *i.e.,* number of grains per unit area, is presented in Figure 4. Figure 4 shows that almost 75% of particles in transport are being carried below 100 mm and 88% below 140 mm. Overwhelmingly, the bulk of the population remains close to the surface; only a small percentage is being lifted above the apparent break. Once again, the separation seems to occur near 120 mm.

It is an observation of the authors that the volume of windblown sand is increased on heavily used beaches, such as on the Gold Coast. This results from the disturbance of the mini-armour layer, which when intact, would significantly inhibit wind transport. Pedestrians can effectively mix up the sand population and expose to the wind sand which would otherwise be unavailable for transport.

SMITH (1992) also deduced that the parameter of F50 specific surface/particle count held some relevance to the *fluvial* transport of sediments so Figure 5 shows the plot for the windblown sand. As can be seen, the mean trend line initially falls and then rises again with a point of contra-flexure at a height of about 90 mm. It is not at all clear what this means, but for a third time the separation of wind-blow into two different zones appears. The separation point tends to vary slightly, but it falls within a quite confined height range, *i.e.,* between say 90 and 100 mm.

The analyses of particle specific surface seem to infer the existence of two different zones of particle transport, but they cannot physically explain why this should be so. Specific surface as a sediment descriptor, combines many different particle parameters including size, shape, mass, and surface texture. Which one, or combination, hold dominance over the others in controlling particle flight cannot be deduced from those particular analyses. In an effort to detect the relative importance of each parameter additional individual analysis on each of the size, shape and weight were performed. Generally these tests detected an interval of values for the airborne sand which differed distinctly from both the surface mini-armour and parent sub-surface layers, but they did not, for the most part, support the existence of a separate bedload and flying load. The results of these analyses are presented in Table 3 and Table 4.

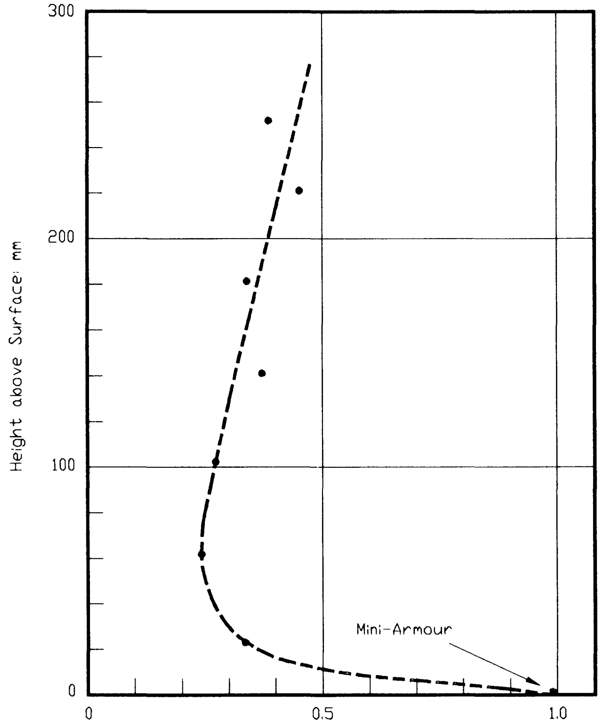

Figure 5. Relationship between height of sample and F/N mobility parameter.

Particle Width

Most discussions of sediment characteristics define a population by its median grain diameter, D50, as determined by the standard sieve test. A sieve test was not feasible for this investigation, so an "equivalent D50" was calculated for each

Table 3. *Sand particle analyses.*

Sample	Specific Surface F50 = mm^2/gram × 10^3	Particle Width (D50 = mm)	Particle Weight (M50 = mg × 10^{2})
Parent	7,200	0.31	4.0
Mini-armour	4,500	0.47	20.00
1	9,600	0.23	2.65
2	12,000	0.26	1.05
3	16,000	0.20	1.30
4	13,500	0.24	1.65
5	16,000	0.20	2.00
6	18,000	0.23	2.25
7	19,500	0.22	1.25

Table 4. *Sand particle shape analyses.*

Sample	Aspect Ratio (A50 = length/width)	Thickness Ratio (T50 = width/depth)	L/D Ratio (L/D50 = length/depth)
Parent	1.15	1.12	1.35
Mini-armour	1.25	1.30	1.75
1	1.84	1.26	2.35
2	1.24	1.33	1.85
3	1.25	1.23	1.65
4	1.27	1.0	1.40
5	1.28	1.0	1.45
6	1.13	1.23	1.30
7	1.20	1.21	1.37

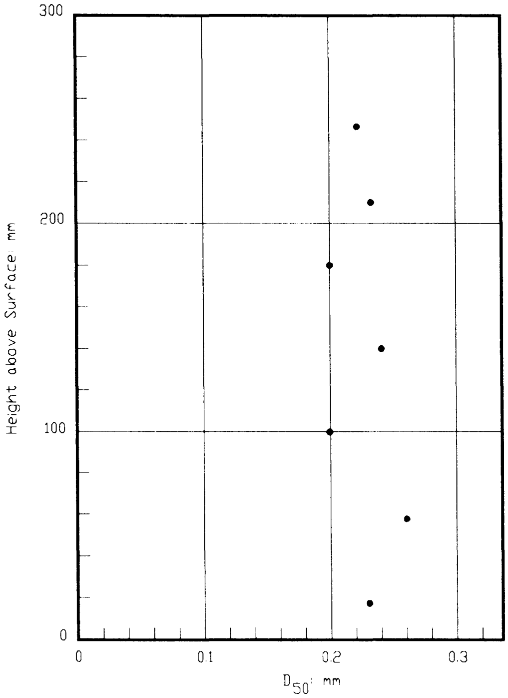

Figure 6. Relationship between D_{50} parameter and height of sample.

sample using the second, or "width" dimension of each grain, as measured under the microscope.

Somewhat surprisingly, particle width data did not produce any populations matching any of the standard probability distributions. Because of this, the D50 values in Table 3 and in Figures 6 and 7 had to be calculated from the raw data percentages instead of graphically.

For the airborne samples, D50 fell between 0.20 mm and 0.26 mm. The parent sample had a D50 of 0.31 mm and the mini-armour a value of 0.47 mm. While the data in Figure 7 shows good separation between the airborne, parent, and mini-armour samples, Figure 6 shows no apparent trend against height within the airborne samples. Nowhere does it suggest that there are two separate zones of transport. The distribution of particle width is apparently quite random.

The plot of Figure 7 measures the importance of particle width against specific surface. Once again, the values of D50 seem to be remarkably random in the airborne population. For example both the F50 and D50 values at intervals 3 and 5 are equal. At intervals 1 and 6, the D50 values are also equal, but the F50 values differ by a factor of two. Clearly, a one dimensional parameter such as D50 is rather unsuitable for explaining three dimensional processes and relationships.

Particle Shape

Three different shape factors were analysed for each sample. The first is the aspect ratio (A), which is the ratio of the particle length to its width, sometimes also referred to as the lift factor. The second is the thickness ratio (T), which is the ratio of particle width to depth. It is also called the drag factor. The third is simply referred to as the "L/D" ratio because there is no common engineering term. It is the ratio of length to depth, or more simply L/D = A × T. In Table 4 the values for each ratio are the median values in the samples. The minimum value of each ratio is 1.0, indicating the dimensions are equal. Objects with a higher aspect ratio will receive the greater lift. Conversely, a higher thickness ratio will result in less drag on the object. The L/D ratio reflects the overall shape of the particle, with 1.0 describing either a sphere or cube, and higher ratios indicating either a disc or rod-shaped particle.

The A50 values seemed to be fairly equal across the samples, falling between 1.13 and 1.28, except in interval one, which had an anomalous value of 1.84. It is not understood why this particular sample with a high lift factor is carried less than 20 mm above the beach surface. Perhaps these particles are significantly heavier than the rest of the airborne particles and so remain close to the surface. This explanation would be supported by the data in Table 3.

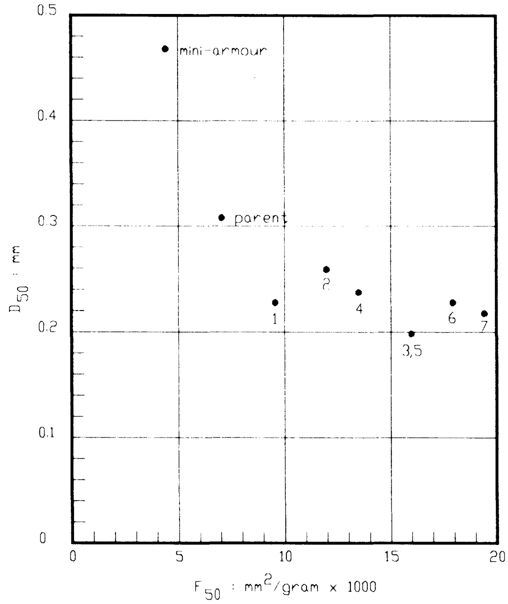

Figure 7. Relationship between F_{50} and D_{50} parameters.

The values of T50 also seemed to be fairly uniform across the total population, ranging between 1.0 and 1.33. Perhaps the issue of import here is that the low aspect and thickness ratios reflect the extensive weathering the population has endured, creating grains of a nearly uniform shape. In both cases, the ratios of the airborne samples differed little from those of the parent and mini-armour samples.

The L/D ratios, however, yielded some surprising results. As Figure 8 shows, there was a marked decrease in L/D with an increase in height. There also appears to be a limiting value of L/D at about 1.3. It appears that the flying load consists of the most spherical grains, and that the more irregular grains are confined to the bedload.

Let us consider once more the perplexity of sample 2, which had the anomalous slope in Figure 1, by factoring in the L/D ratio. The L/D ratio (1.85) for Sample 2 is considerably higher than the samples collected at greater heights.

According to GOLDSMITH (1985), irregularly shaped grains generally bounce less than spherical grains, explaining the high L/D ratios of samples 1, 2 and 3. What still needs explanation is why the ratio of the mini-armour (1.75) is similar to those in the bedload but that of the parent sample (1.35) agrees with those in the flying zone. Our only guess is that this sorting only affects those particles actually in transport.

It should also be noted that in most discussion of beach sediment it is assumed that all sand grains are spherical—the use of D50 (the D stands for "diameter") implicitly assumes this. Our shape factors show this is clearly not the case. A total of only 17%, ranging from 2% to 28%, had a "spherical" L/D ratio of 1.0. This is actually a significant fraction of the total population considering the range of natural variability, but it does not merit any universal assumption.

Particle Weight

Weight, as described in the previous section, seems to be less important to a particle's transportability than its shape. However, we performed an analysis on weight just in case it did demonstrate some physical trend.

The M50 of each sample is in Table 3. For the airborne samples, M50 fell between 105 and 265, significantly different from the parent M50 and 400 and the mini-armour M50 or 2,000.

M50 showed a peculiar trend of *increasing* with height, with the exception of sharp breaks in samples 1 (height = 20 mm) and 7 (height = 245 mm). As stated earlier, this is probably explained by the fact that large particles bounce higher that small particles, but this trend directly conflicts with Figure 2—which indicates that the particles became *finer* with height. The size hypothesis can only be supported by our measurements of *mass,* as our D50 graph showed no trend whatsoever. It seems more likely that the particle shape, as supported by measurements of specific surface and L/D, plays a larger role than mass, but our data are far from conclusive.

Mass is clearly prominent in keeping the mini-armour and parent population immobile until a wind with greater energy is able to lift them into transport. It may also be important just above the beach surface (20 mm), but to a lesser extent. Shape appears to quickly assume dominance once the particles are airborne. The observation that grains adhered to the tape "end on" also supports the importance of particle shape, upon how the grains actually fly.

Bagnold describes in some detail the mechanism by which windblown sand deposition occurs in graded layers with the coarsest material overlying the fine material. Likewise, a surface lag of coarse material is found also at the source of sand removal. This readily explains the observation of the mini-armour of coarse particles on the beach surface. This "inverse grading" is important in distinguishing eolian deposits from fluvial or marine deposits in the geologic record. Bagnold's description in based largely on field observations, but he makes little mention of it in his experiments. This could be due to the removal of the coarse tail in his sand populations.

At this stage it may be reasonable to compare the apparent behaviour of the beach windblown sand considered above with the definitive work of BAGNOLD (1942) on desert windblown sand. In some aspects there are close similarities, but in others there appear to be significant differences. The first step is to compare the source of data. Bagnold's basic studies were conducted in a 200 × 300 m wind flume (presumably using real desert sand) whilst this beach study collected travelling beach sand directly on the prototype. Then in his wind tunnel, Bagnold used sand that had been sieved to give a nominal "size" range of 0.30 mm to 0.18 mm with a mean "size" of 0.24 mm. The Gold Coast beach sand also held a sieve D50-0.24 mm, but it remained a full natural population, *i.e.,* it had not been cropped in any way. In terms of simple D50 sieve values, the two populations might well be regarded as equivalent, but in real performance they should be expected to be rather different.

The most striking similarity between both these studies appears to lie with the behaviour of the near-ground saltating sand particles. With pebbles on the ground surface Bagnold found that his *maximum* particle bounce height was 1,200 mm for an "equivalent" wind velocity of 12.5 m/sec and an 0.3 mm spherical particle. If Bagnold's maximum bounce height is factored for the beach sand in proportion to a velocity of 5.6 m/sec squared and a particle diameter of 0.24 mm cubed, then the beach particle *bounce* should not exceed 120 mm assuming that the beach mini-armour acted in the same manner as surface desert pebbles. Figures 2, 3 and 5 all demonstrate a major change in the windblown beach sand particle population properties, at, or near to, this point. It would seem reasonable therefore to conclude that what is called "bedload" on these diagrams is in fact the total saltating population on the beach.

What was then collected above this level on the beach is not saltating particles but fully airborne material—here called the "flying load" population, or, in Bagnold's terms, a true (?) suspension. That this flying load was not detected in Bagnold's wind tunnel is probably due to the use of a sand with its fine tail removed—and also due to the wind boundary layer deceleration of the air flow against the *roof* of the tunnel. On the beach the wind velocity would be increasing continually with height; there would be plenty of wind energy available to transport particles well above the saltating zone.

This would also explain why the sand particle populations in the flying load zone are very different from the saltating, bed-

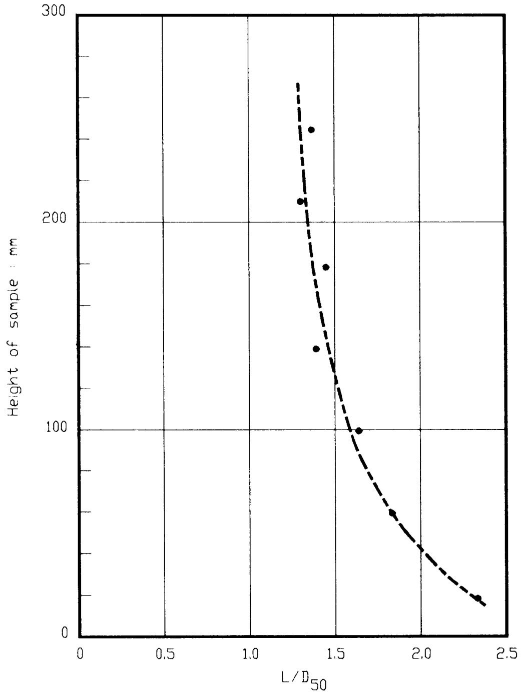

Figure 8. Relationship between L/D parameter and height of sample.

load populations. Fully suspended flying particles would be sorted quite differently from bouncing particles, their energy *absorption* mechanisms would be quite unlike. This factor tends to show up in Figure 1 as the change in slope of the relevant specific surface plots. Table I shows that in general the particle F50 specific surface tends to increase with height, *i.e.,* the particles are finer—which is exactly as might have been expected, but there are some apparent anomalies that remain. The particle F value does take into account the particle mass, surface area, shape and texture, but the plot of Figure 2 still indicates that it is not capable of providing an indicator of the real transportability of sand grains in air—the flying and bedload populations overlap. The F50/N plot of Figure 5 appears to be a little better. The L/D plot in Figure 8 seems to be the most promising, but it is clearly not yet precise enough. There appears to be still something seriously missing.

CONCLUSIONS

We initiated this study, based upon capturing all the sand grains in the air and at exactly their location above the beach at the time and upon measuring all the shape and weight factors of every grain in a binocular microscope. From this we hoped to be able to identify the particular particle shape factors that controlled the flight location of the grains together with their vertical sorting, but in this we have largely failed. We have discovered little "positive" evidence of correlations, but a great deal of "negative" evidence *i.e.,* most of the particle shape, weight and ratio parameters we investigated clearly do not describe the actual airborne wind supported sediment population, as we collected it. Certainly for a population that might have consisted largely of saltating grains, each grain would be traversing up and down most of our individuals sticky tape "capture" panels, but within the total capture time (120 seconds) and the number of grains, this factor should have been averaged out, but quite simply, we do not know, if it was or not. The height to which any particular particle might bounce into saltation depends not only upon its own mass and shape, but also upon the mass and shape of the much larger mini-armour particle that it bounded off and this inter-relation must be extremely variable and indeterminate with time, and affected by the falling angle of approach of the saltating grains.

Nevertheless, whether our study produced "positive" or "negative" correlation evidence, we still think that we do have something worth reporting. Thus, we might summarise our conclusion to date as:

(1) Based upon the parameter of Specific Surface, that does integrate all physical individual grain properties, aerial transport appears to occur in two distinct strata, a near surface saltating zone and a higher "flying" zone where all particles are in suspension.
(2) A coarse layer of "mini-armour" develops very rapidly on the beach surface as the wind preferentially carries away the finer grains.
(3) The specific surface of the sand grains tends to increase with height above the beach indicating that the particles are unequivably fining upwards. The visual D50 values do now show such a fundamental trend.
(4) The L/D shape factor tends to decrease upwards, indicating that irregular particles tend to be confined within the near-ground transport, whilst the most symmetrical particles tend to migrate into the flying load.
(5) The aspect and thickness ratios show no apparent trend.
(6) Particle individual weights seem to be of significance only within the mini-armour and parent populations.

So what *have* we found? What we have found is only that same old story, that all natural coastal processes, in the overall, are remarkably complex and fraught with great uncertainty, within space and time. We can only marvel at the original work of BAGNOLD (1942), that was so definitive, that 60 years after his research was concluded, we have hardly progressed onwards at all, and least of all, all of us. As we continually have to report about our long term coastal process research upon the Gold Coast of Queensland, we still have a very long way to go!

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