Particle size and sorting characteristics of sand in transport on the stoss slope of a small reversing dune

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Abstract

Studies of the particle size and sorting characteristics of sand on the stoss slope of a 6-m high reversing dune show that the sand in transport is generally finer and better sorted than surface sand at the same position on the slope. The sand in transport becomes coarser and more poorly sorted as wind speed and rates of mass transport increase toward the dune crest. These patterns reflect changes in the competence of the wind, which is capable of transporting larger grains and a wider range of grain sizes as its speed increases in space and time. Our field observations suggest that the particle size and sorting characteristics of surface sand are highly dependent on antecedent wind conditions and are not an invariant property of the dune, as is widely assumed. The wide range of particle sizes on the surface, as well as its change through time, also has important implications for modeling sediment transport on dunes. Transport thresholds may vary by as much as 30% on the stoss slope of the study dune.

Keywords: Aeolian processes; Sand particle size and sorting

1. Introduction

The particle size and sorting characteristics of the surface sands of aeolian dunes have been studied by numerous authors, many of whom have documented spatial variations in size and sorting characteristics, as reviewed by Pye and Tsoar (1990) and Lancaster (1995). Models for such variations have been developed by several workers, including Folk (1970) and Lancaster (1981, 1986). These models seek to explain changes in mean particle size, sorting and other statistical parameters in terms of differential rates of movement of sand grains of varying sizes by creep, reptation and saltation. For example, coarser grains are mainly transported by creep and reptation resulting from the impact of finer saltating grains and may travel slowly compared to the finer particles. The coarse grains remain in lower slope positions on the dune, so that the surface sands in these areas are relatively coarse and poorly sorted compared to fine well-sorted crest and upper slope sands (Lancaster, 1981).

Studies of the particle size and sorting characteristics of aeolian dune sand in transport are, by con-
trast, rare, especially those that compare the characteristics of the surface and transported grains. Most prior studies are concerned with the transport of fine-grained material (silt and clay) (e.g. Gillette et al., 1974; Nickling, 1983) or the vertical distribution of grain size in transport in laboratory wind tunnels (Williams, 1964) or field studies (Chen and Fryrear, 1996).

This paper documents spatial variations in the particle size and sorting characteristics of sand in transport on the windward (stoss) slope of a small (~6 m high) reversing dune as a contribution to understanding the spatial variability in the particle size and sorting characteristics of surface aeolian sands. We deal with a situation in which the primary modes of sediment transport are creep/reptation and saltation.

2. Experimental procedures and methods

The studies were conducted on the slopes of a small reversing dune in the western part of the Silver Peak dunefield of west central Nevada (Figs. 1–3). The dune is 80 m long and 6 m high with a sharp crest aligned transverse to the prevailing north and south winds. The aspect ratio of the stoss slope is 0.11 (Fig. 3C). Similarly shaped 4-m high reversing ridges lie to the north and south of the study dune. During the period of study (May 1994), the winds reversed direction from northerly to southerly on several occasions so that the orientation and height of the lee face changed. Maximum lee face height was 1.5 m, oriented to the south.

The primary goal of the study was to investigate the structure of surface airflow and sediment transport across the dune (McKenna Neuman et al., 1997). Sixteen cup anemometers were deployed at a height of 0.3 m on a transect across the dune. A passive wedge-shaped sediment trap (Nickling and McKenna Neuman, 1997) was installed close to each anemometer site, alternating to the E and W of the anemometer transect by 1.5–2 m to minimize interference with airflow (Fig. 2). The traps were oriented to the local ripple crests on the dune surface, and approx-

![Fig. 1. Location of the Silver Peak dune field and the study dune.](image-url)
imately parallel to the local airflow. An entrance lip prevented scour around the trap nozzle without affecting the entry of saltating and reptating grains into the trap. The sand surface within 0.2 m of the sides and rear of the trap was stabilized by light wetting with a spray bottle to prevent scour in these areas. The collection period (typically 10–20 min) ended when the traps at the crest were filled to capacity (~1200 g).

The sediment collected in the sand traps during three runs was saved for particle size analysis. If more than 100 g was collected in a sand trap, the sample was split mechanically to give a subsample of approximately 100 g. If the sand trap collected less than 100 g, then all the sand was sieved. A sample of surface sand was collected adjacent to each trap location after all the experiments were completed and winds had restored the surface to an undisturbed condition. An area of approximately 0.25 m² was scraped with a trowel to a depth of 0.01 m and the sand placed in a bag for subsequent analysis. These samples were subdivided mechanically to provide a 100-g sample for sieve analysis.

All sand samples were sieved in a nest of sieves at 0.5 intervals for 10 min. Folk graphical particle size and sorting parameters were calculated using the program GRANNY (McLane, 1989).

3. Results

Fig. 3A shows that wind speed at a height of 0.3 m varies across the dune in a similar way for each of the three runs. Winds increased slightly from 5–7 m s⁻¹ at the toe of the dune to 7–8 m s⁻¹ 10 m upwind of the crest, and then increased sharply in the region of the upper dune slope. Speed-up factors ranged from 1.33 (Run 1) to 1.63 (Run 8). Measured rates of sand transport (Fig. 3B) remained at low to moderate values (<0.05 g cm⁻¹ s⁻¹) until approximately 30 m from the toe of the dune, and then increased rapidly on the upper stoss slope to 0.4–0.5 g cm⁻¹ s⁻¹ (Fig. 3B). Full details of the measurements and discussion of the relations between sand transport rates and winds during this experiment are presented in McKenna Neu- man et al. (1997).

3.1. Sand in transport

Fig. 4 shows representative particle size distributions of sand collected by sand traps located in low, mid and upper slope positions. The modal particle size in each case is 2.5 φ (180 μm). The percentage of sand in the 1.5 and 2.0 φ (710 and 500 μm) classes increases up slope, whereas the proportion in the 3.0 φ (125 μm) size class decreases up slope. Sand collected in the sand traps exhibits significant changes in particle size and sorting characteristics on the stoss slope but comparatively little variation from one run to another (Fig. 5).

Mean grain size (Fig. 5) remains quite constant at 2.3–2.4 φ (203–189 μm) across the lower stoss slopes of the dune to within 10 m of the crest and then changes abruptly to 1.90–2.0 φ (268–250 μm) at the crest. Sand in transport, therefore, becomes coarser toward the dune crest. Values of inclusive graphic standard deviation (σ) (sorting) improve up
the stoss slope of the dune (Fig. 5), from values around 0.6 (or moderately sorted) at the toe to 0.44–0.46 (well sorted) about 6 m from the crest. Sorting values then increase (sorting is poorer) from this point to the crest, where values are in the range 0.60–0.70 (moderately sorted). Skewness values

Fig. 3. (A) Variation in wind speed at 0.3 m during the periods studied. (B) Variation in sand transport rate over the dune during the same periods. (C) Topographic profile of the dune stoss slope.
(Fig. 5) change from slightly negatively skewed \((-0.1\) to \(-0.2\)) on the lower stoss slope to nearly symmetrical at the crest \((-0.002\) to \(-0.004\)). Overall, a pattern of increasing mean grain size, poorer sorting, and decreasing negative skewness occurs toward the dune crest. As observed elsewhere (Lan caster, 1995), sorting improves with decreasing mean grain size, so that sand in transport is better sorted as it becomes finer (Fig. 6).

3.2. Surface sand

Fig. 7 shows representative particle size distributions for surface sand collected from the same sub-environments as selected for the trapped sands. Crest and upper slope sands are dominated by sand in the 1.5–2.5 \(\phi\) (355–350 \(\mu\)m) size classes. The proportion of sand in the 3.0–4.0 \(\phi\) (125–90 \(\mu\)m) and 0.5 and 1.0 \(\phi\) (500–710 \(\mu\)m) classes increases from the lower slope towards the crest of the dune.

The grain size and sorting characteristics of the surface sands also change over the dune and tend to be somewhat more irregular than the transported sand (Fig. 5). With the exception of a patch of coarse, relatively poorly sorted sand on the lower slope, mean grain size (Fig. 5) increases slightly from 2.1 to 2.0 \(\phi\) (233–250 \(\mu\)m) on the lower stoss to 1.80 \(\phi\) just before the crest. Sorting values (Fig. 5) generally decrease from 0.80 near the toe to 0.50 at the dune crest. Skewness values exhibit considerably less overall change and become more positively skewed towards the dune crest (Fig. 5). As with the sand in transport, there is a strong relation between the mean grain size and sorting of the surface sands so that finer sands are better sorted than coarser sands (Fig. 6).

Comparison of the size and sorting characteristics of the transported sand with that of the surface sand (Figs. 5 and 6) indicates that the sand in transport is almost always finer and better sorted than the surface sand on the stoss slope. The transported sand is also generally more negatively skewed than surface sand at the same location. The modal size group of the surface sand is 2.0 \(\phi\) (250 \(\mu\)m) on the entire stoss slope, but more sand occurs in the 2.5 \(\phi\) size class on the lower parts of the dune. The modal size groups of sand in
Fig. 5. Variation in mean grain size, sorting and skewness of sand in transport on the stoss slope, with surface sand grain size and sorting parameters shown for comparison.
transport are 2.5 and 3.0 φ (180 and 125 μm) with the 2.5 φ mode dominating. Our field observations support the model put forward by McLaren and Bowles (1985) in which the transported material is usually finer and better sorted than the surface from which it is derived.

4. Discussion

Although considerable scatter exists in the data, the mean grain size of sand in transport tends to increase (Fig. 5), sorting becomes poorer (Fig. 5) and the particle size distribution becomes more symmet-
tical (Fig. 5) as wind speed and, therefore, rates of sand transport increase toward the dune crest.

In interpreting these data, we assume that the sand traps used in this study collect a representative sample of the sand in transport and that they do not under- or over-sample any range of particle sizes. The trap design was thoroughly tested in a series of detailed wind tunnel tests and was shown to be near isokinetic with a very high sampling efficiency (> 90%) for a wide range of wind velocities (Nickling and McKenna Neuman, 1997). Calculation of saltation trajectories assuming a lift-off angle of 50° and an initial vertical velocity of \(0.63 u_*\) (Shao, 2001), for a range of particle sizes indicate that trajectory height is typically less than 0.01–0.025 m and is not nearly as sensitive to grain size as it is to lift-off angle and retained particle speed. The modeled height of the saltation cloud, therefore, lies well within the physical dimensions of the trap intake. Similarly, from examination of the ratio \(u_f/u_*\) (Pye, 1987) for the strongest wind events observed in this study, the possibility of even very fine sand grains travelling in short term suspension around the trap inlet can be eliminated. We therefore have reason to believe that the sand traps used in this study collected a representative sample of the grains in transport and that no systematic bias exists in the size of grains entering the trap.

Given these assumptions, the relations between wind speed, rates of sand transport and the size and sorting of grains in transport suggest that, as its speed increases, the wind is capable of transporting larger grains and a greater range of grain sizes, as noted by Sharp (1964). This is reflected in the larger mean grain size and poorer sorting at locations on the dune characterized by higher rates of sand transport (Fig. 8). The relation between mean grain size and the rate of sand transport is a reflection of the competency of the wind to transport particles of a given size. Provided that a range of particle sizes are available for transport, increasing wind speed and rates of transport will also result in a greater range of sand sizes in transport, therefore, leading to a decrease in sorting. As wind speed and transport rates increase up the dune (Fig. 3), an increase in the mean size of sand in transport and an associated decrease in sorting should occur. Near the toe of the stoss slope, however, there is both a wide range of grain sizes available for transport and a low competency of the wind. This results in relatively poor sorting of sand in transport in this region, as indicated in Fig. 5.

The Silver Peak dunefield is located close to its sand sources, which for the most part are believed to be distal alluvial fan deposits. This dunefield, therefore, contains significant amounts of coarse grains that are available for transport by strong winds. This is unlike so-called “mature” sand seas (e.g., central Namib Sand Sea), which lie at some distance in time and space from the original sources of sediment.

The availability of a wide range of sand particle sizes in this dunefield exerts a strong influence on the temporal and spatial patterns of particle size and sorting in the surface sand and sand in transport by wind. Previous models (e.g., Lancaster, 1981; Folk, 1970) indicate progressive fining of sands toward dune crests resulting from differential transport rates of slow-moving coarse and faster-moving fine grains. These models suggest that coarse grains remain in lower areas of dunes because insufficient wind energy exists to move them to higher positions. Our field observations show that coarse grains are found in lower slope and crestal areas of dunes at Silver Peak, a pattern which is not adequately explained by available models.

An alternate explanation lies in the dynamics of the sand transport process on these dunes. In lower areas of the dune, the wind speed is frequently low (5–7 m s\(^{-1}\)) and intermittently above transport threshold. Saltation in these areas has low energy and the magnitude of transport rate is low with correspondingly low creep and reptation transport rates. The sand in transport is, therefore, relatively fine and contains a small range of particle sizes (well sorted), but the surface sand becomes progressively coarser because of winnowing of the fine grains. During periods of strong winds, some of the coarse sand is transported up the dune to areas where wind velocity is higher and above transport threshold, leading to high-energy saltation at relatively high rates. This high-energy saltation drives the reptation and creep of larger grains to the crest. Sand in transport is, therefore, relatively coarse and somewhat more poorly sorted, but surface sand is finer, with a small tail of coarse grains. During periods of low or moderate winds, any coarse grains that are transported up the dune remain in place and the surface sands tend to be coarser than the sand in transport.
Our observations suggest that the particle size and sorting characteristics of surface sand sampled at any point in time and space are highly dependent on antecedent conditions and are not a constant property of the dune, as has been widely assumed. Surface sands sampled after a high wind event will have a different spatial pattern of particle size and sorting characteristics compared to those sampled after periods of low winds. The pattern of grain size and sorting described above reflects the combined effects of the sand transport events sampled and is, therefore, characteristic of this period of time. Different patterns would be expected if the surface sand was sampled after a period of gentle winds.

These findings have important implications for modeling sediment transport on dunes and that transport threshold must be an important component of models for sand transport. Our observations indicate that a wide range of mean grain size occurs on the stoss slope of the study dune, which is associated with a range in the threshold shear velocity, calculated using the equation of Bagnold (1941), from 0.23 m s$^{-1}$ at the toe of the dune to 0.30 m s$^{-1}$ at the crest. This represents a 32% increase in threshold on the stoss slope, as compared to a 16% increase because of slope effects, as reported in our 1997 paper (McKenna Neuman et al., 1997). Based on values of shear velocity reported by McKenna Neuman et al. (1997)
for this dune, ignoring spatial changes in particle size could result in overestimates of transport rates at the dune crest in the order of 20–30%. Further, values of transport thresholds have a significant effect on the index of wind strength (Stout and Zobeck, 1997) and, therefore, the intermittency of sand transport. Our studies on this dune have shown the importance of intermittency to modeling of spatial and temporal variability of rates of sand transport rates (McKenna Neuman et al., 2000).

5. Conclusions

The grain size and sorting characteristics of transported sand on dunes reflects the competence of the wind and the textural characteristics of the surface sand. This study suggests that the grain size and sorting characteristics of the surface sand vary in space and time and reflect antecedent wind conditions. This has important implications for modeling rates of sand transport on dunes and further illustrates the nonlinear dynamics of aeolian sediment transport systems.

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