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The saltations of different sized particles in aeolian sand transport

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ABSTRACT

Wind tunnel experiments were performed in order to investigate the effect of mixing on the aeolian transport of sands with different grain sizes. Two types of sand with different grain size distributions and an equal-mass binary mixture of these sands were used. Comparing the gradients of their measured mass flux profiles and some published profiles for mixed sand transport with those for nearly uniform sand transport, it was found that for both of these types of sand bed, the negative gradient of the mass flux profile on a log-linear plot varies with the mass averaged grain size of the sand bed according to the same power law. Hence it can be deduced that, during the aeolian transport of mixed sand beds, the mean vertical ejection speeds of different sized grains are nearly identical to that for the transport of monospecific-sized sand with the same mass averaged grain size. Theoretical analysis was undertaken to explore the characteristics of ejections of different sized grains during the aeolian transport of sand with mixed-size grains. It is proposed that the mean ejection angles and the mean ejection speeds for sand grains of different sizes are nearly identical and are equivalent to that for monospecific-sized sand with the same mass averaged grain size. It was also evident that the ratio between the transport rate of each grain size group expressed as the fraction in the whole transport rate and its mass fraction in the mixed-size sand is a combined consequence of both the wind effect on the mean saltation distance of different sized grains and the effect of the mass fraction of each grain size group in the original mixture on its ejection potential responding to an impact of a saltating sand grain.

1. Introduction

Aeolian sand transport is an important physical process that can result in severe environmental disasters (e.g. sandstorm, desertification). Consequently, it has attracted increasing attention over past decades and considerable research has been carried out to examine this transport process. The relationships between macro-variables (such as sand mass flux and sand transport rate) and transport conditions (such as wind velocity and bed surface characteristics) have been explored, but have only been described by empirical or semi-empirical models (Bagnold, 1941; Owen, 1964; Dong et al., 2003; Sørensen, 2004). To investigate the intrinsic mechanisms of sand transport, a great deal of effort has been devoted to exploring the coupling mechanism between saltation particles and wind flow (Ungar and Haff, 1987; Werner, 1990; Anderson and Haff, 1991; McEwen and Willetts, 1991; Spies and McEwan, 2000), and to understanding the energy exchange during the collision between sand grains entrained in air and those on the bed surface or the ejection behavior of sand grains from bed surfaces by wind tunnel experiments, grain-bed collision experiments and numerical simulations (Anderson and Haff, 1991; Werner, 1990; Nalpanis et al., 1993; Dong et al., 2002b; Ammi et al., 2009).

Previous theoretical analyses of aeolian sand transport have normally assumed that the sand is a monodisperse system. However, sand beds in the field generally have a wide grain size distribution. Experimental studies using wind tunnels and in the field have mainly focused on the vertical distribution of the statistical variables, such as mean grain size, standard deviation and skewness (Sharp, 1964; Williams, 1964; Nickling, 1983; Chen et al., 1995; Arens et al., 2002). Recently, the modeling of saltation of variously sized particles in a mixed-size sand transport has been paid more attention. Attempts were made to model the saltation of different sized particles theoretically (Shao and Mikami, 2005) and numerically (Kok and Renno, 2009), but the ejection characteristics of different sized grains and the relationship between them are still unclear and are assumed empirically in these models. Xing (2007) conducted a wind-tunnel experiment using mixed sand beds, in which the vertical distribution of the mass flux profiles of different grain size groups was found to be similar and their slopes on log-linear plots were nearly equal. Furthermore, Xing (2007) proposed a semi-analytical relationship between the transport rates of different grain size groups with the original grain size distribution of the sand. In order to establish a quantitative relationship between the transport of different grain size groups, it is essential to examine their interaction mechanisms, especially the mechanisms of energy propagation in the splash process

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and the ejection of different sized grains. However, this aspect has been largely ignored in past research except for a few attempts in exploring the ejection characteristics of different sized particles for mixed-size sand. Anderson and Bunas (1993) proposed in their 2D numerical simulation that the smaller grains were preferentially ejected from the bed. Rice et al. (1995) observed the typical ejection speeds and angles of the three types of sand with different size ranges in a wind tunnel experiment, and proposed that their ejected mass ratios seem to be proportional to their initial mass ratios in the bed. Using a 2D simulation of grain-bed collision with a particle dynamic method, Li and Zhou (2007) suggested that the grain size distribution of ejected particles is similar to that of the initial bed. However, exploration of this aspect is very inadequate and there still exists great controversy about the ejection of different sized grains. Therefore, further investigation of the relationships of ejection speeds, ejection angles and dislodgment rates between different sized grains is essential to fully understand and model mixed-size sand saltation.

In this paper, the experimental data of mass flux profiles for two types of sand with narrow size ranges and a binary mixture of these two sand sizes are reanalyzed and compared to the mass flux profiles of uniform sand transport to investigate the effect of the initial grain size distribution on the mass flux profiles of different grain size groups, and thus on their ejection behaviors. Based on these results, a theoretical analysis of mixed-sand saltation is performed. Combining the theoretical analysis with experimental results, an insight into the ejection behaviors of various sized grains in aeolian sand transport is provided.

2. Experimental

Experiments were conducted to examine the spatial distribution of different grain size groups and to analyze their ejection behavior accordingly. The transport characteristics of the two types of sand beds with different grain size distributions and their binary mixture were tested. The measured data have been shown in a previous paper (Xing, 2007). Here, attempts were made to explore the effect of mixing on the motions of different sized grains by reanalyzing these data in a different way.

The sand used was predominantly quartz with a density of 2588 kg/m^3. Two types of sand were prepared by sieving with coupled sieves of different mesh sizes: they are denoted *Sand No. 1* and *Sand No. 2* for convenience. *Sand No .3* was prepared by mixing Sand No. 1 and No. 2 with equal mass fractions. The grain size distributions of the three types of sand were determined using an optical microscope in conjunction with an image analysis system. Since the grains were irregular in shape, the size was evaluated by the Feret diameter and the values are shown in Fig. 1. The mass averaged grain sizes of the three sand samples were 525, 364 and 421 μm respectively.

The experiments were carried out in a blow-type wind tunnel (Fig. 2). The cross-sectional dimension of the test section in the wind tunnel is 0.40 m (W) × 0.60 m (H). A Pitot tube was set at the centerline of the entrance to the test section in order to measure the free-stream wind velocity. The blown sand flux was measured by a segmented sand trap that was set 4 m downstream from the entrance of the test section of the wind tunnel. The base of the lowest opening of the sand trap was set flush with the tunnel floor. The sand bed upstream of the sand trap was 4 m long, 0.4 m wide and 3 cm deep. The wind tunnel was first activated for 3 min and then the trap was removed to collect the sand in each chamber, which was weighed by using an electronic balance with a resolution of 0.01 g. The grain size distribution of the sand in each chamber was analyzed by measuring more than 500 grains using the microscope and image analysis system. The measurements were carried with air velocities of 8.5, 10.5, 12.5 and 14.5 m/s. A detailed description of the wind tunnel and measurement method can be found in Xing (2007).

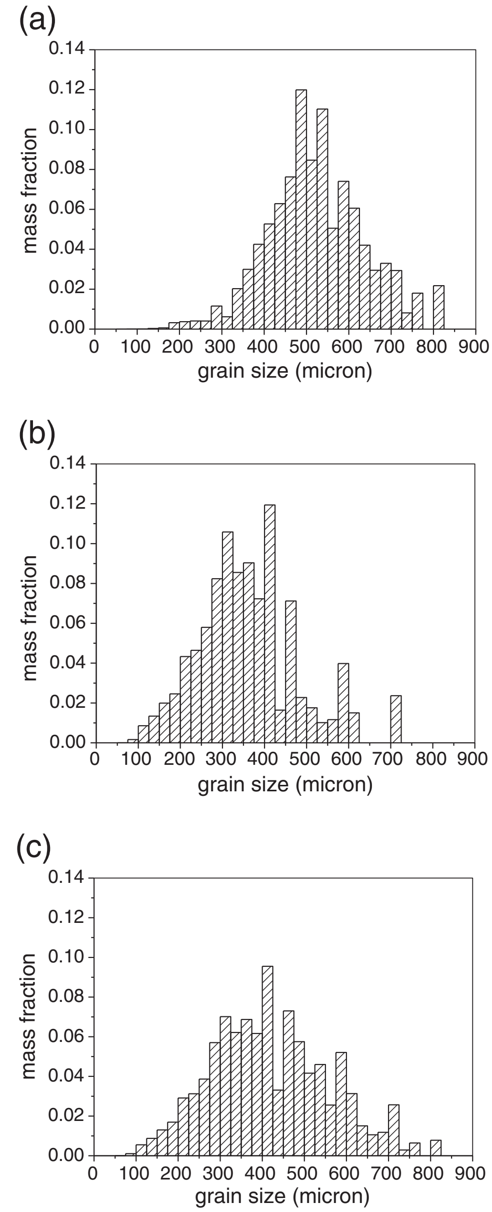

Fig. 1. Grain size distributions of the test sands: (a)–(c) are sand No. 1–No. 3, respectively.

3. Results and discussions

3.1. Sand mass flux profiles

The sand weights from each chamber of the trap were converted to horizontal mass flux $q(z)$ with units of kg m^{-2} s^{-1}. The vertical profiles of horizontal mass flux at four wind velocities are shown in Fig. 3. It can be seen that all mass flux profiles $q(z)$ decay exponentially with height above 2 cm from the bed since the data can be fitted by straight lines on a log-linear plot, which is consistent with other experimental observations (Bagnold, 1941; Butterfield, 1999). It is also clear that at a given wind velocity, the gradient of the mass flux profile for Sand No. 3 is intermediate between those for Sands No. 1 and No. 2. That is, the transport of the binary sand mixture No. 3 shows an average characteristic between those of the two components.

Dong et al. (2002a) measured the mass flux profiles for sand transport of nearly monospecific-sized sand and presented the profile gradients on log-linear plots for different sized sand at different wind velocities. Their results showed that the gradients increase significantly