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Influence of slope gradient on the behavior of saltating sand particles in a wind tunnel

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ABSTRACT

Current theoretical and experimental studies of windblown sand movement are mostly conducted on flat sand surfaces. However, sand dunes, basic forms of desert landscapes, have slope gradients that greatly influence the transportation of sand particles. In this study, sand velocity on the windward and leeward slopes of barchans dunes was measured using a laser Phase Doppler Particle Analyzer in a wind tunnel. Our results measured from slope are quite different from existing data of flat surface. The average velocity of sand particles increased from bottom to top of the windward slope. And the particle velocity on leeward slope is not greatly impact by position and wind speed. Unlike exponential decay on flat bed, the lift-off angle on windward slope shows left-skewed distribution with a single peak, and the distribution of impact and lift-off angle on leeward slope are entirely different from those obtained on flat bed. On the leeward slope, impact and lift-off angle were affected remarkably by the position on the slope. On the leeward slope, the number of particles with wind direction horizontal velocity is basically the same as those of particles with headwind direction horizontal velocity. The vertical and horizontal turbulence intensity reached the maximum when the particles were located 20 mm from the bed surface near the bottom of leeward slope; and the minimum at 60 mm from the bed surface. Both vertical and horizontal turbulence intensity of particles increased with increasing wind velocity. The increase in the horizontal turbulence intensity was greater than the increase in the vertical turbulence intensity. The findings from this study would provide a better understanding of movement of blown sands over sand dunes and mechanism underlying the formation of sand dunes.

1. Introduction

Blown sand is a common and natural phenomenon occurring near earth surface (Anderson and Haff, 1988, 1991). Sand particles on the bare surface are lifted up by external forces such as wind and the impact of other particles, then accelerated constantly in the air and fall down under the action of gravity, finally transferring the momentum obtained from the wind field to the surface by impacting the ground, which at the same time may rebound or splash other surface particles to form even larger blown sand movement (Anderson and Haff, 1991). The wind-blown sand movement near the ground surface is the direct cause of desertification, which not only affects land degradation, change topography, but also is one of the important factors that impact industrial and agricultural production, transportation security and the global climate change (Wu and Wang, 2003; Shao, 2008; Van Pelt and Zobeck, 2004; Kang and Liu, 2010).

Aeolian saltation accounts for 3/4 of total sand movement and is the major movement of windblown sand (Bagnold, 1941). Therefore, research on aeolian saltation is considered to be an important topic. A better understanding of saltating particles' movement furthers our knowledge on mechanisms of aeolian processes. Because of the individuality of moving particles, it is really hard to reveal the characteristic of group-movement of wind-blown sand based on the information of one single particle. Since 1980′s, after the International Congress of Aeolian Research in Aarhus, Denmark, it is using the micro motion characteristics of single particles to analyze and explain the overall wind-blown sand movement that has become the focus of studying wind-blown sand movement near the ground surface (Wu et al., 2013). Characterization of the particle velocity distribution is in fact the link between the micro and macro wind studies (Cheng et al., 2006; Kang and Zou, 2013). As early as in 1977, White and Schulz (1977) tried to observe and analyze the movement of glass beads with a density close to sand particles using high-speed photography in a wind tunnel. Subsequently, Mitha et al. (1986) used steel beads to replace quartz sand to investigate the relationships among lift-off speed, lift-off angle, incident angle, and incident speed. Rice et al. (1995) studied the distribution of velocity of

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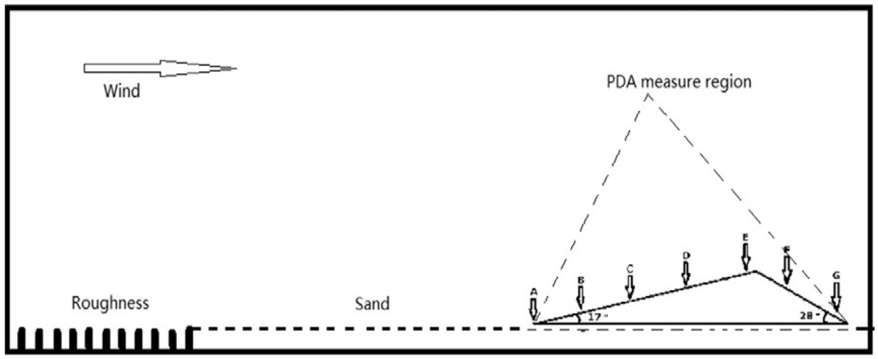

Fig. 1. Side view of a wind tunnel experiment.

three artificial sands during splash process. Zou and Wang (2001); Dong and Wang, 2002; Dong et al. (2001, 2002, 2004), and Kang et al. (2008a, 2008b) Carried out a wind tunnel experiment to analyze the distributions of particle velocity with different angles in the saltation layer, by using the PDPA.

However, so far, most of experimental works have been focused on aeolian saltation on flat surface (Zheng et al., 2005; Greeley et al., 1996). Kang et al. (2008a, 2008b) indicates that the shapes of ascending and descending particles' distribution have a typical peak. Greeley et al. (1996) used the high-speed motion pictures to give a result that the velocity distributions of ascending and descending grains show a single peak. Little data on distribution of velocity of saltating sand grains is available from experiments conducted in complex surface conditions that are closer to real-world situations. Kocurek and Lancaster (1999) showed that the flow field distribution over height on front slope of dunes is no longer simply logarithmic when measured on windward slope. Compared with flat surface, wind- blown sand movement is expected to show different characteristics in complex terrain conditions (Wiggs, 2001). A better understanding of velocity distribution of saltating sand grains on slope conditions will greatly help to reveal the development and disappearance of wind- blown sands, transportation and sediment of sand particles, and impact intensity of saltating particles in field condition Kang et al. (2008a, 2008b).

2. Experimental equipment and principle

Phase Doppler Particle Analyzer (PDPA) is a non-contact optical measuring method based on laser Doppler Effect. It does not interfere flow field and has high measurement accuracy, and has been increasingly used in experimental observation of sand movement near ground surface Kang et al. (2008a, 2008b). PDA's main working principle is that a laser beam emitted by the laser generator is separated into two parallel coherent beams by a splitter. Through the lens, the two coherent beams intersect at one point (measurement point) and form alternative bright and dark interference fringes at the cross point. The distance between the fringes is dependent on the wavelength and angle of the incident laser. When particles are travelling through the interference fringes at the measurement point, the receiver receives the light signals with changing intensity scattered from the particles and converts them into Doppler signal. Through the analysis of Doppler signal, the time with which the particles travel through the alternative bright and dark fringes can be determined, and consequently the speed of particles perpendicular to the direction of the interference fringes calculated.

The experiment was carried out in a multifunctional tunnel in the Key Laboratory of Western China Disaster and Environment Mechanics, Lanzhou University. The wind tunnel is 22 m long, 1.45 m section high and 1.3 m section wide. The front part of the experimental section was arranged with rough elements to accelerate the development of the thickness in boundary layer. The thickness of the air flow boundary layer at the measurement position could be as high as 0.65 m. The velocity of free stream in the tunnel can be adjusted from 4 to 40 m/s continuously. A triangle dune model with the angles of 17° and 28° in the windward and leeward slopes, respectively, and height of 0.178 m was used to mimic complex surface. The model was placed 7 to 8 m from the rough elements (Fig. 1), in order to reach the dynamic stability of aeolian sand flow at the measurement points. Seven measurement points were set up around the model with five on the windward (Point A, B, C, D, E) slope and two on the leeward slope (Point F, G) (Fig. 1) at height of 5 mm from the bed surface.

Sand used in the experiment were natural sand taken from Minqin region at the junction between the Tengger Desert and Badan Jilin Desert. Measurement with PDA showed that the distribution of the particle size was logarithmic (Fig. 2) with the mean size of 0.2618 mm.

To confirm the similarity of flow fields between the flow-field environment in the wind tunnel and field wind-field in atmospheric boundary layer, the Pitot tube was used to measure the wind velocity profile of clear flow-field under the flat surface condition in the wind tunnel prior to the experiment. The results are shown in Fig. 3. Similar to the neutral atmospheric boundary layer in the open field, the distribution of average wind velocity along the height (wind profile) in the wind tunnel also satisfied the following logarithmic law:

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \quad (1)$$

where $u\,(z)$ is horizontal wind speed at height of z; u^* is friction velocity; Z_0 is surface roughness; k is the Von Karman constant (~0.4).

The wind velocity profile in the tunnel near the ground was logarithmic, indicating that the tunnel was well suitable to stimulate the

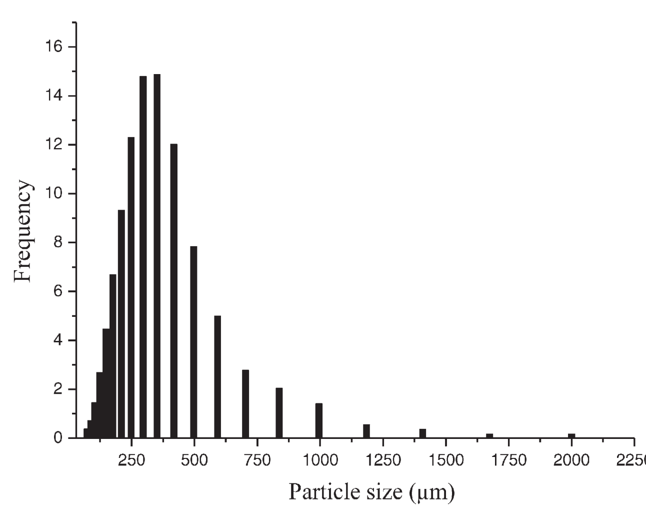

Fig. 2. Frequency of distribution of particle size.