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Trajectories of saltating sand particles behind a porous fence

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ABSTRACT

Trajectories of aeolian sand particles behind a porous wind fence embedded in a simulated atmospheric boundary layer were visualized experimentally, to investigate the shelter effect of the fence on sand saltation. Two sand samples, one collected from a beach ($d = 250$ μm) and the other from a desert ($d = 100$ μm), were tested in comparison with the previous studies of a 'no-fence' case. A wind fence ($\varepsilon = 38.5\%$) was installed on a flat sand bed filled with each sand sample. A high-speed photography technique and the particle tracking velocimetry (PTV) method were employed to reconstruct the trajectories of particles saltating behind the fence. The collision processes of these sand particles were analyzed, momentum and kinetic energy transfer between saltating particles and ground surface were also investigated. In the wake region, probability density distributions of the impact velocities agree well with the pattern of no-fence case, and can be explained by a log-normal law. The horizontal component of impact velocity for the beach sand is decreased by about 54%, and about 76% for the desert sand. Vertical restitution coefficients of bouncing particles are smaller than 1.0 due to the presence of the wind fence. The saltating particles lose a large proportion of their energy during the collision process. These results illustrate that the porous wind fence effectively abates the further evolution of saltating sand particles.

1. Introduction

Saltation is the primary mechanism of aeolian sand transport in which sand particles make continuous bouncing motions across the surface during wind erosion (Bagnold, 1941). These sand transport motions cause serious environmental problems, such as the diminution of agricultural land areas and the formation of large sand seas or individual sand dunes (Shao, 2008). These desertification processes have a negative impact on human habitats, and has given rise to serious land deterioration of three centers of population across the globe in human history: the Mediterranean, the Mesopotamian Valley, and the loess plateau of China (Dregne, 1985). Nowadays, it has been estimated that the total area between 6 and 12 million square kilometers are under threat from desertification (World Bank, 2009). Therefore, accurate and detailed description of the saltation process and development of an effective means to control saltating sand are important.

In general, a typical saltation process is subdivided into four components: (i) aerodynamic entrainment, (ii) grain trajectory, (iii) collision process between particles and sand bed, and (iv) wind modification (Anderson et al., 1991). Among these components, the collision process, also termed "splash", is responsible for the transfer and dissipation of energy in granular flows (Herrmann et al., 1998). During a splash process, saltating particles with high kinetic energy hit the sand bed surface and then rebound back to the air with new particles ejected into saltation. Subsequent energy transfer occurs between the saltating particles, ejected particles, and sand bed surface. Some of the energy is used to excite the re-emission of the saltating grain, as well as the ejection of other grains (Rioual et al., 2000). Therefore, an understanding of this process is crucial in explaining the development of saltation clouds.

The collision process has been investigated by several researchers. Rumpel (1985) mentioned that the angle of rebound is roughly around 50° rather than 90°, as assumed by Bagnold (1941). Willetts and Rice (1985) observed that the incident grain hits the ground surface at a small angle in the range of 10°–16°, and then bounces with an angle in the range of 20°–40°. Nalpanis et al. (1993) found that the probability distributions of the resultant lift-off velocity and angle are well fitted with the log-normal law. In recent years, non-intrusive measurement techniques, including laser Doppler anemometry (LDA), particle image velocimetry (PIV) and particle tracking velocimetry (PTV), have been developed for more accurate measurement of particle movements (e.g., Liu and Dong, 2004; Yang et al., 2007; Zhang et al., 2007a; Rasmussen and Sorensen, 2008; Creyssels et al., 2009; Cheng et al., 2009). Among these techniques, PIV yields a full-field flow information and simultaneously measures particle velocities and concentration within the cross-section of the flow. This advantage can break through the limitation of single-point measurement of LDA technique, and make it possible for the test of two-phase aeolian sediment transport

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(e.g., Zhang et al., 2008; Yang et al., 2011; Bo et al., 2014). However, the result of PIV method is essentially an average of the interrogation area between two consecutive image frames, and can hardly track a whole saltation process of exactly the same particle. Therefore, it is almost impossible to tell exactly when and where the particle collides with the sand bed on the basis of a PIV outcome. By contrast, the PTV method is valid for visualizing the whole trajectory of every single saltating particle, and is capable of providing more detailed information on the splash dynamics of sand particles (e.g., Baek and Lee, 1996; Gordon and Neuman, 2011).

Although many studies have investigated the splash process, few of them have focused on the control or abatement of sand saltation. Among protection methods, a porous wind fence with certain porosity serves as an artificial barrier to reduce wind-blown particle sediments by decreasing the speed of the oncoming wind. The porous wind fence has been widely used in coastal, arid and desert areas (Bagley, 1988). Its shelter efficiency is usually evaluated based on the velocity deficit in the wake behind the fence. Previous studies (e.g., Raine and Stevenson, 1977; Perera, 1981; Ranga et al., 1988; Lee and Kim, 1998, 1999) showed that the reduction in wind velocity by a porous fence strongly depends on the fence porosity, and porosity (ε) in the range of 0.3–0.4 is the most effective both in decreasing wind speed and in abating the recirculation bubble in the wake region. In addition, Dong et al. (2007, 2010) employed a PIV system to measure instantaneous velocity fields behind a vertical fence. This PIV method is useful in measuring the spatial distributions of mean velocity, turbulence intensity, and shear stress of the flow around the fence. However, information in the wake flow is insufficient to predict all the characteristics of saltation across the wind fence. For this purpose, additional information on the motion of saltating particles is needed.

Besides the wake flow characteristics of porous fence, its shelter effect on sediment transport was another interest issue. However, due to non-proportional scale reduction of fence and particle size, the sand movement downstream of a porous fence was almost impossible to simulate in the wind tunnel experimental test, thus very few studies focused on direct measurement of sand saltation behind a fence. Cornelis and Gabriels (2005) observed the deposition of saltating particles on the ground surface behind a wind fence. Dong et al. (2006) measured the threshold wind speed of saltating sand for wind fences with different porosities. Tsukahara et al. (2012) discussed the erosion process of sand dune model on the shelter of a porous fence, by visualizing the sand saltation movement in the wake flow. All these results were obtained by observing the amount of particles deposited on the surface, but detailed trajectories on saltating sand particles was not obtained. The movement of saltating sand particles around the wind fence can be observed using PTV method along with a high-speed camera. In our previous study (Zhang et al., 2010), instantaneous velocity fields of saltating sand particles were extracted, and saltating parameters, such as mean velocity, volume concentration, mass flux and kinetic energy, were simultaneously evaluated.

This study aims to reconstruct the trajectories of saltating sand particles in the region behind a porous fence using high-speed photography. With the obtained experimental data on saltating motion, a statistical analysis was performed to extract the probability density distribution of each impact parameter, and variations in sand particle deposition were compared with previous studies. The relationship between rebounding particles and their incident angles was also examined to reveal the shelter effect of the porous fence on controlling the erosion of aeolian sand particles.

2. Experimental apparatus and techniques

2.1. Experimental set-up

Experiments were performed in an open-type subsonic wind tunnel with a test section of 6.75 m × 0.72 m × 0.6 m (l × w × h) in dimensions. Spires (0.28 m high) and artificial grass (0.5 m long) were installed at the entrance of the test section to simulate a neutral simulated atmospheric boundary layer (ABL). The velocity profile of the oncoming wind fits well with a logarithmic distribution expressed as follows:

$$\frac{U(z)}{u_*} = \frac{1}{k} \ln\left(\frac{z}{z_0}\right) \tag{1}$$

where $U(z)$ is the streamwise mean velocity at a height z, u_* is the friction velocity, κ is the von Karman constant, and z_0 is the effective roughness. The turbulence intensity defined as $\sqrt{\overline{u'^2}}/U \times 100$ is about 10% near the ground surface ($z = 0$). It gradually decreases as z increases. Details of the velocity profile measurement are described in Zhang et al. (2007a).

Fig. 1 shows a schematic diagram of the wind tunnel test section and the measurement system. Two sand samples were tested: grains with a mean diameter of 250 μm collected from a beach and grains with a mean diameter of 100 μm collected from a desert. Although aeolian sediment transports are both common in desert and beach region, wind-speed thresholds for sand movement are different due to the differences of grain size grading. The 100 μm sand was sampled from the Taklimakan desert, and also reported in several researches in this field (e.g., Zhang et al., 2007a, 2007b, 2008; Yang et al., 2011; Tsukahara et al., 2012). The 250 μm sand was compared to 100 μm sand to show the influence of grain size in the test. Each sample was spread evenly onto the sand bed over an area 1600 mm × 220 mm × 10 mm (l × w × h). A porous wind fence model, 30 mm high and 560 mm long with a porosity of 38.5%, was installed at the center of the sand bed. The porous fence was made of 0.3 mm thick stainless steel plate, and the holes, with diameters of 1.4 mm, were precisely drilled using an etching technique. The shape ratio (thickness/height) was 0.01. The flow around it could be regarded as a thin fence flow because the shape ratio was less than 0.33.

The saltating particles were illuminated using a 300 W xenon lamp from the back side of the test section with a set of convex lenses and mirrors (Fig. 1). This experimental set-up is helpful in preventing strong light scattering from the sand surface. A high-speed CMOS camera (FASTCAM-APX) was employed to capture images consecutively at a high frame rate of 2048 fps. The field of view (FOV) was fixed at 76 mm × 38 mm for all measurements in the vertical center plane. A total of 4096 frames were consecutively recorded for each run, and three runs were repeated for each sand sample. Zhang et al. (2007b) performed a sand saltation measurement of no-fence case by using the same experimental apparatus and sand samples, and found that a moderate range of free stream velocity should be from 4.5 $m.s^{-1}$ to 8.05 $m.s^{-1}$ for fully developed saltation in this test. However, the splash process becomes difficult to observe with a large concentration of sand saltation very near the bed. To avoid noise disturbance between the images of saltating particles, the experiments for the beach sand were performed at a free stream velocity (U_0) of 7.0 $m.s^{-1}$; for the desert sand, $U_0 = 6.0$ $m.s^{-1}$. This is consistent with the wind-tunnel experiment by Zhang et al. (2007a), which also performed a statistical analysis of the splash process without the fence model using the same sand samples. In their test, the free stream velocity was 7.05 $m.s^{-1}$ for beach sand, and 5.5 $m.s^{-1}$ for desert sand to guarantee the balance between the image quality and sufficient particle number for statistical analysis.

2.2. Image processing

By overlapping a sequence of consecutive images, each trajectory of sand colliding with the ground surface was reconstructed to provide statistical analysis of the kinematic features, (see example in Fig. 2a). The sample number of particle trajectories was guaranteed to be more than 300, which can provide a statistically robust result. This limitation number was based on a previous research on the statics of windblown sand flux (Zhang et al., 2007c). It should be noted that all the trajectories were reconstructed at the condition with relatively low concentration of