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Fall velocities of saltating sand grains in air and their distribution laws

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ABSTRACT

In a cloud of blowing sand, collisions between falling sand grains and the sand bed are an important process that is the main source of additional saltating sand grains, because the collision process transfers momentum to the sand bed and initiates the liftoff of new sand grains. The initial liftoff and fall velocities of saltating sand grains are key parameters in the collision process, but little information exists on the subsequent fall velocities of the saltating sand grains. One important reason for this lack is that the collision process is unclear. Based on experimental data from high-speed multi-flash photographic images obtained in a wind tunnel and on a motion model of saltating sand grains, this paper discusses the fall velocities of saltating sand grains and the corresponding velocity frequency distributions. The results demonstrate that fall angles are small (less than 20°), and decrease with increasing frictional wind velocity. The vertical component of fall velocity increases with increasing frictional wind velocity, and is consistent with the initial vertical liftoff velocity. The fall angle and vertical velocity both follow a gamma distribution. The horizontal fall velocity mainly determines the resultant fall velocity, and both increase with increasing frictional wind velocity. The horizontal and resultant fall velocities follow a Pearson IV distribution. These results improve our understanding of the collision process between falling sand grains and sand beds and will also help us to modify the splash function that connects the parameters of falling saltating sand grains and their initial liftoff parameters.

1. Introduction

Aeolian sand flow is a special case of a two-phase gas–solid flow that results from spatial displacement of sand particles by the wind [1]. The solid phase is asymmetrically distributed, and the basal plane (here, the sand bed) often changes in response to wind and particle collisions. In addition, many direct and indirect factors influence the process in nature, and experimental conditions have thus far prevented detailed and accurate observations of near-bed saltation. Therefore, scientists have divided the behavior of saltating sand grains into several sub-processes (jumping of the sand grains, movement of sand grains in the airflow, changes of the airflow due to the presence of the moving sand grains, and collisions between falling sand grains and sand grains in the underlying sand bed) or have focused on key parameters such as initial liftoff velocities, liftoff rates, and fall velocities. This approach greatly simplifies the complex problem of how to model the movement of blowing sand, and makes it possible to develop models of each sub-process. Furthermore, it is convenient to research aeolian sand movement by combining the abovementioned sub-processes and key parameters. As a result, researchers have carried out many studies of these sub-processes [2–15] and parameters [16–29], thereby improving our understanding of the movement of blowing sand and accelerating development of the physics of blowing sand. However, no current model does an adequate job of fully characterizing the movement of blowing sand.

It is well known that the liftoff of sand grains in a cloud of blowing sand is accelerated by the airflow and that the sand grains continuously obtain energy from the airflow. That energy is subsequently transferred to the ground surface by the collisions between falling sand grains and the sand bed. Therefore, the fall velocities of saltating sand grains and their distributions are key parameters in determining how the collision processes lead to the development of saltation clouds and to their subsequent behavior. These characteristics also modify the splash function that connects the initial liftoff parameters of sand grains and their subsequent fall parameters. Thus, the impact velocities of saltating sand grains are important indicators that reflect the trajectories of saltating sand grains and determine the overall sand flux that develops above the bed [27]. At a seminar held at Aarthus University in 1985, scholars began to recognize that the distribution function for the initial liftoff velocities of saltating sand grains has great significance, and that it is a bridge between microscopic and macroscopic research on the physics of blowing sand. Since then, great progress has been made on the probability distribution for the initial liftoff velocities of saltating

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sand grains [2,4,8,10,11,17,19,25,30–36]. The research has improved our understanding of the motion of blowing sand, but large differences persist between experimental observations and the results of theoretical simulations. One reason for this discrepancy is the disproportionate amount of attention that has been paid to initial liftoff velocities of saltating sand grains, and the corresponding lack of data on their fall velocities. This has made it difficult to clarify details of the collision process between falling sand grains and sand grains in the underlying sand bed.

Despite the disproportionate amount of attention that has been paid to initial liftoff velocities, some research has investigated the fall parameters of saltating sand grains [2,4,5,7,10,19,27,31,37]. However, most of these researches have only described the fall angles of the saltating sand grains rather than their fall velocities, and there has been even less quantitative discussion of the distribution laws that describe the fall parameters of saltating sand grains. Generally, fall angles have ranged between 10° and 30° [2,4,16,19,20,34], while Dong et al [38] reported that fall angles vary widely (between 0° and 180°) based on the observation parameters of the motion of saltating sand grains very near the surface level (about 1mm above the bed) by means of particle dynamics analysis, and proposed that there is a backward-collision between falling sand grains and sand grains in the underlying sand bed. In addition, some researchers discussed the relationship between liftoff angles and fall angles. For example, Yang [10] and Dong et al. [37] reported that fall angles increased linearly with increasing liftoff angles. In contrast, Zou et al. [39] performed a theoretical analysis that suggested there would be a linear relationship between the cotangent of the fall angle and the cotangent of the initial liftoff angle. Most researchers have concentrated on the relationship between the fall velocities of sand grains and their initial liftoff velocities [7,9,30,31,37,40] or the frictional wind speed [13].

Several collision experiments have shown a strong correlation between the initial liftoff velocities of saltating sand grains and their fall velocities, including the rebound of the saltating sand grains and the splash of sand grains out of the sand bed [7]. Rebound velocities of saltating sand grains are typically about 0.50 to 0.60 times their fall velocities, whereas splash velocities for sand grains leaving the sand bed are approximately 0.08 to 0.10 times the fall velocities of the saltating sand grains [7,37]. Dong et al. provided a mathematical expression ($\ln(V_{\mathrm{liftoff}})=1.0324+0.3558V_{\mathrm{fall}}^{0.5}$) for the mean liftoff and impact velocities. Zhang et al. [13] reported that the vertical fall velocity is only 0.69 to 0.86 times u_* (the frictional wind speed), and is about 10% of the horizontal fall velocity; the mean resultant fall velocity ranges from 4.33 to 8.33 u_*. On the whole, there has been little research on fall velocities [4–5, 10, 13, 37–38, 41] and only 3 papers discuss the probability distribution laws of fall velocities [10,37,38]. One study of the frequency distribution of fall velocities suggested that the fall angles of the sand grains roughly followed a skewed normal distribution [4]. Based on a two-body impact model, Yang [10] hypothesized that the horizontal, vertical, and resultant fall velocities followed an exponential distribution, but did not propose mathematical expressions to describe this distribution. Based on the movement parameters of saltating sand grains at the near-surface level (1 mm above the bed), obtained using particle dynamics analysis, Dong et al. [37] reported that the probability distribution of the fall speeds of saltating sand grains followed a Weibull distribution. Based on the vertical distribution of sand flux as a function of height [33] and an empirical power function for the relationship between the velocities of sand grains and their height above the bed [1], Dong et al. [38] reported that the resultant fall velocities of saltating sand grains followed a modified exponential distribution.

Based on this review of the literature, it is clear that considerable progress has been made on characterizing the fall velocities of saltating sand grains, and that the results are helping researchers to understand aeolian sand movement. However, the collision process is not yet adequately understood. Experimental conditions have failed to produce sufficient numbers of near-bed saltating grains, or observations have not recorded the behavior of sufficient grains, and previous researchers have often confined their studies to a specific wind velocity due to the intrinsic complexity of studying the relationship between wind velocity and aeolian sand movement. It remains necessary to study the fall parameters of saltating sand grains and their distributions in more depth to further improve our understanding of the physics of blowing sand. The purpose of the study described in the present paper was to discuss the fall velocities of saltating sand grains and their characteristics based on the calculated fall parameters (the horizontal, vertical, and resultant components of velocity and the fall angle) based on experimental data obtained by means of high-speed multi-flash photography in a wind tunnel and based on a motion model of saltating sand grains. The results will help invert the collision coefficient between falling sand grains and the sand bed and to modify the splash function that connects the initial liftoff parameters of saltating sand grains with their fall parameters.

2. Methods and materials

2.1. Wind tunnel experiment

The experiments were conducted in the wind tunnel of the Institute of Desert Research, Chinese Academy of Sciences. The wind tunnel is 37.78 m long, and the experimental section is 16.23 m long, 1.0 m wide, and 0.6 m high. The wind velocity at the central axis of the wind tunnel can be continuously varied between 2 and 40 m s^{-1}, with turbulence intensity lower than 0.4% [1]. To ensure significant development of the saltation layer over the sand bed, we spread a 6-m-long, 3- to 5-cm-thick layer of sand on the floor of the wind tunnel's experimental section. The diameter of the sand grains used in this study ranged from 0.2 to 0.3 mm, with a mean grain size (D) of 0.25 mm and a basic density of 2650 kg m^{-3}. Experiments were conducted at 22 °C at night under three frictional velocities (u_*): 0.67, 0.77, and 0.87 m s^{-1}.

We used a Japanese-made MS-230 light source as a high-speed multi-flash light to form a 1-cm-wide light spot that vertically irradiated the sand bed from the top of the wind tunnel. We used a FUJICA-135 camera, with an aperture set at f/1.9, and Chinese-made 27DIN Lucky panchromatic film. The exposure time and flash speed were selected based on the demands of our experiment. To photograph the movement of the sand grains, the flash speed was set at 400 s^{-1} and the camera exposure time was 0.5 s [1]. To photograph the rotation of the sand grains, we used the same flash to provide light, but with a single exposure time of 0.002 s. A more detailed description of the wind tunnel experiment is provided in references [1] and [15].

2.2. Motion model for the saltating sand grains

To simplify our calculations, we described the movement of sand grains in an x–z coordinate system (where x represents the axis parallel to the airflow direction and z represents the axis perpendicular to the wind tunnel's floor). During the saltation process, sand grains are affected by the interactions among effective gravity (G), which results from the interaction of gravity with air buoyancy, aerodynamic drag (F_{d}), the Magnus force (F_{m}), and the Saffman force (F_{s}). The expressions of these forces are described in references [15], [29], and [36]. Assuming that there is an angle (α) between the direction of sand movement and the direction of the airflow in the x–z plane. Falling sand particles move travel vertically and horizontally, and v_{r} is the "resultant" velocity of the sand grains that represents the combined effect of the vertical and horizontal velocity components; $v_r=\sqrt{(u-v_x)^2+v_z^2}$ and represents the relative velocity of sand grains with respect to the air flow, where v_x and v_z are the horizontal and