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Aeolian sand transport: Length and height distributions of saltation trajectories

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ABSTRACT

We report wind-tunnel measurements on aeolian sand transport aiming at characterizing the distribution of the length and height of trajectories of the saltating particles. We employ a simple horizontal sand trap device to assess the distribution of saltation length while the distribution of saltation height is inferred from the measurements of the particle lift-off velocity by means of particle velocimetry tracking techniques. Our measurements reveal that the saltation length and height present a continuum distribution which decreases monotonously and exhibits a long tail that can be well described by a lognormal law. Interestingly, these distributions are found almost invariant with the flow strength. As a consequence, the mean saltation length ($\bar{l}$) and height ($\bar{h}$) are independent of the flow strength confirming previous indirect measurements. The influence of the flow strength is only seen through the tail of the saltation length distribution: the higher the Shields number, the flatter the distribution tail. Finally, experiments carried out with sand of different sizes show that the mean saltation length and height are not related to the sand grain size through a simple manner but depend instead linearly with the height z_f of the Bagnold focus point: $\bar{l} \approx 6z_f$ and $\bar{h} \approx 0.6z_f$. This last result emphasizes that the focus height is an important characteristic length scale of the saltation transport.

1. Introduction

The transport of sand and dust by wind is a major mechanism contributing to landform evolution in coastal environment, deserts and agricultural fields. It also plays an important role in environmental problems including soil erosion, nutrient dispersion, dust storms and desertification. Sand transport by wind is a complex process including air-particle and bed-particle interaction which was first documented by Bagnold in 1941 (Bagnold, 1941). He identified in particular the key feature of aeolian transport, that is the so-called saltation process. Saltation is the main mode of transport in which sand grains are propelled by the wind along the sand bed and travel via successive jumps. On the basis of the saltation mechanism, Bagnold derived a law for modeling aeolian transport rates,

$$Q = A_B \frac{g}{\rho_{\text{air}}} u_*^3, \quad (1)$$

where u_* is the wind shear velocity defined as $u_* = \sqrt{\tau/\rho_{\text{air}}}$ (τ being the basal wind shear stress). He also identified a particular height where the air velocity is independent of the wind shear stress. This point was termed later the Bagnold focus point and is defined via the wind velocity profile $U(z)$:

$$U(z) = U_f + \frac{u_*}{\kappa} \ln \frac{z}{z_f}. \quad (2)$$

z_f is the height of the focus point and U_f is the wind velocity at that height which is invariant with the wind strength. It is worth recalling that Eq. (2) holds only for height z greater than the focus point. Below the focus point, the air velocity profile is almost invariant with the air friction speed u^*.

Since then and particularly within the two last decades, a multitude of field and wind-tunnel studies (Willetts and Rice, 1986; Willetts and Rice, 1989; Nalpanis et al., 1993; Greeley et al., 1996; Namikas et al., 2003; Liu and Dong, 2004; Rasmussen and Sørensen, 2008; Creyssels et al., 2009; Ho et al., 2011; Ho et al., 2012) and theoretical works (Werner, 1990; Anderson et al., 1991; Sørensen, 1991; Creyssels et al., 2009; Kok and Renno, 2009) have been carried out to refine the understanding of the aeolian transport process. Thanks to the improvement of imaging techniques (e.g., Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV) (Creyssels et al., 2009)), it is possible now to get a more accurate description of the saltation cloud. In particular, recent wind-tunnel experiments (Liu and Dong, 2004; Rasmussen and Sørensen, 2008; Creyssels et al., 2009) provide a

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rather accurate characterization of aeolian transport in terms of particle velocity and concentration within the saltation layer. The most salient features drawn from these recent experiments can be summarized as follows (Ho, 2012). First, the particle velocity profile within the saltation layer is almost insensitive to the wind shear stress. In particular, below the focus point (i.e., $z < z_f$), the mean horizontal particle velocity increases linearly with increasing height as:

$$u(z) = u_0 + \gamma z, \tag{3}$$

where the slip velocity u_0 and the shear rate γ are insensitive to the wind strength but may depend on the grain size. Moreover, the mean vertical velocity of ascending and descending particles is almost uniform within the saltation layer. Second, the particle concentration increases with increasing wind speed and follows a universal law (Ho, 2012):

$$\nu(z) = \nu_0 f(z/l_\nu) \tag{4}$$

with

$$\nu_0 \approx \alpha(S - S_d) \tag{5}$$

$$l_\nu \approx 1.2 z_f \tag{6}$$

where ν_0 is the particle concentration at the bed surface. The concentration is expressed in terms of the solid volume fraction (i.e., the ratio of the solid volume of the granular phase to the volume that it occupies). f is a universal function which asymptotically approaches an exponential behavior at large height (i.e., $f(z/l_\nu) \approx e^{-z/l_\nu}$ for $z > l_\nu$), l_ν is the characteristic decay height of the particle concentration, $S = \rho_{air} u_*^2 / \rho_p g d$ is the Shields number, and S_d the critical Shields number corresponding the dynamic threshold of saltation transport. The parameter α is a constant of order of 0.1 and depends on the grain diameter (Ho, 2012). The salient result (Creyssels et al., 2009; Ho, 2012) lies in the fact that the characteristic decay height l_ν is almost invariant with the wind shear stress and is of the same oder of magnitude as the focus height z_f. This means that the focus height is closely related to the vertical extent of the saltation layer. We should mention however that the above results have been obtained in a finite range of Shields number from 0.04 to 0.2. It is not excluded that at higher Shields number the decay height l_ν may increase significantly.

Interestingly, Eq. (5) tells us that the particle volume fraction at the bed surface increases linearly with the Shields parameter. An important consequence of these findings is that the overwhole mass transport rate, which can be obtained by the vertical integration of the product of the particle velocity, $u(z)$, and the particle volume fraction, $\nu(z)$, scales linearly with the Shields parameter (or quadratically with the shear velocity) (Ho et al., 2011):

$$Q = A_H \rho_p d \sqrt{gd}(S - S_d) = A_H \sqrt{\frac{d}{g}} \rho_{air}(u^{*2} - u_d^{*2}), \tag{7}$$

where A_H is a constant which depends on the grain size. This result contrasts with the Bagnold cubing scaling but it is explained by the fact that the particle velocity within the saltation layer is almost insensitive to the wind strength as first suggested by Ungar and Haff (1987) and later confirmed experimentally by Creyssels et al. (2009) and Ho et al. (2011). In addition to the mass transport rate Q, the vertical mass flux at the bed, Φ_0, is an other important quantity regarding soil erosion issue. The latter, which is obtained by the product of the particle volume fraction and the vertical velocity of the ascending (or descending) particles at the bed, scales linearly as well with the Shied parameter (Ho, 2012):

$$\Phi_0 = B_H \rho_p \sqrt{gd}(S - S_d) = B_H \frac{\rho_{air}}{\sqrt{gd}}(u^{*2} - u_d^{*2}), \tag{8}$$

where B_H is a constant which again depends on the grain size. The transport rate Q and the vertical flux Φ_0 at the bed surface are closely connected. As shown later on in the paper, we have the following relation:

$$Q = \bar{l}\Phi_0, \tag{9}$$

where $\bar{l}$ is the average hop length of the saltating particles. Combining the above results (cf. Eqs. (7) and (8)), we arrive at the conclusion that the mean saltation length $\bar{l}$ should be invariant with the wind strength as evidenced by indirect measurements in Ho et al. (2011).

The above results were obtained from Eulerian approaches (through PTV or PIV techniques). With these techniques one can only assess local quantities such as particle velocity and concentration. These techniques are unfortunately unable to provide direct information on the particle trajectories such as the length and height of the saltating trajectories. Considering the above results, it would be however highly desirable to assess the distribution of the saltation length and height and determine how the moments of these distributions compare with the height z_f of the focus point.

Lagrangian approaches aiming at characterizing the trajectory of saltating particles are much less numerous than Eulerian ones. Such experimental studies have been conducted using either stroboscopic method (White and Schulz, 1977; Willetts and Rice, 1988; Nalpanis et al., 1993) or high speed imaging (Rice et al., 1995, 1996; Zhang et al., 2007). As for PIV or PTV techniques, the scene is illuminated with a laser sheet aligned along the main flow direction. Lagrangian approaches are however subject to operational requirements. First, the tracking of individual trajectories requires in general low seeding. Second, the assessment of the whole distribution of the saltation length and height requires an observation window with large enough dimensions. This requirement may be in conflict with the resolution needed to detect with a reasonable accuracy the successive positions of the saltating particles. Third, the saltating particles have usually a slight transverse velocity component (i.e., perpendicular to the air flow direction) and thus stay a finite time within the laser sheet. This prevents us from tracking the whole saltation trajectory. Enlarging the laser sheet width allows to follow the particle trajectories over a longer time but increases, at the same time, the number of saltating particles in the image thus making the tracking more difficult. These limitations thus impose to work at moderate wind shear stress (close enough from the transport threshold) where the mass flux is reduced. Besides, these techniques present a systematic bias in the statistical analysis of the saltating trajectories. The largest measurable saltation length is limited by the window size while the smallest one by the image resolution. It is indeed in general difficult to resolve the trajectories of the weakly energetic saltating particles which experience small jumps. Close to the sand bed surface, the high particle concentration makes it difficult to track small trajectories.

We provide in this article an alternative method to get the distribution of the saltation length based on classical sand trap devices. This method provides a simple and accurate tool to determine with accuracy the saltation length distribution for arbitrary flow strength and any type of sand. Within this method, we investigated the saltation length for two types of sand (i.e., fine and coarse sand respectively with a mean diameter $d_{fine} = 230\ \mu m$ and $d_{coarse} = 630\ \mu m$) and various flow strength ranging from the critical shear velocity to more than five time this value. These measurements were complemented by the determination of the distribution of the vertical particle lift-off velocity from which we infer the distribution of the saltation height using a numerical model.

The article is organized as follows. In Section 2, we present our wind-tunnel facilities as well as the experimental methods to assess the distribution of saltation length and height. In Section 3,