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The characteristic of streamwise mass flux of windblown sand movement

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ABSTRACT

Two patterns have been reported in previous literature about the streamwise mass flux of windblown sand movement in steady state; namely, the exponential pattern and the stratification pattern. Although the exponential pattern has been verified by some experimental measurements and numerical simulations, an agreed conclusion is not reached yet. Re-evaluating the previous model, it can be found that the pattern of the PDF (probability density function) distribution of the initial liftoff velocity is the key factor that determines whether the stratification happens or not. If the number of liftoff grains decreases with the increase in liftoff velocity, such as in the case of the exponential distribution, the stratification pattern will not appear. If the number of liftoff grains increases first and decreases later with the increase in liftoff velocity, such as in the case of the log-normal distribution, Gamma distribution and Gaussian distribution, the stratification pattern will come into existence. In addition, the hop height for the initial liftoff velocity, corresponding to the peak value of its PDF distribution, equals the height of the maximum streamwise mass flux. On the basis of some deterministic laws from experimental measurements and numerical simulations of grain/bed impact, a qualitative understanding about the PDF distribution of the liftoff velocity is obtained and the Rayleigh distribution is used for reptating grains. Also included in this paper is a model in which grain/bed impact is discussed and the interaction between the grains and the wind is considered. It is shown that the stratification pattern, composed of a linear increment layer, a saturation layer, and a monotonic decrement layer, indeed exists in the streamwise mass flux of windblown sand movement. Further, as with the average velocity and PDF distribution of the liftoff velocity of the reptating grains, which is determined by the characteristics of grains, the height of the peak value of the streamwise mass flux is also determined by the property of the grains and will be independent of the wind intensity.

1. Introduction

Windblown sand movement is responsible for aeolian landforms, deflation and soil erosion. The dominating transport mechanism in windblown sand movement is saltation (e.g., Bagnold, 1941; Anderson et al., 1991; Almeida et al., 2006). The saltating grains can travel a long distance by successive jumps and have sufficient energy to splash other grains when they impact the bed. These splashed, reptating grains, contribute to the augmentation of the sand flux, and some of them can become saltating grains through successive rebounding (e.g., Andreotti, 2004). However, quantitatively, this process is far from being understood (Anderson et al., 1991; Almeida et al., 2006).

For more than half a century, many researchers paid their attention to windblown sand movement to understand and predict the process of saltation. For instance, Anderson and Haff (1988, 1991), McEwan and Willetts (1991, 1993), Zheng et al. (2006) and Ren and Huang (2010) have conducted numerical studies on the evolution of the windblown sand movement. Other macroscopic quantities, such as the streamwise sand transport and wind velocity profile, have also been studied in respect of experiment, simulation and theory to explain the empirical findings (e.g. Owen, 1964; Ungar and Haff, 1987; Anderson and Haff, 1988, 1991; Werner, 1990; White and Mounla, 1991; Iversen and Rasmussen, 1999; McEwan et al., 1999; Namikas, 2003; Andreotti, 2004; Dong et al., 2004; Sørensen, 2004; Almeida et al., 2006; Duran and Herrmann, 2006; Huang et al., 2006; Kok and Renno, 2008, 2009; Rasmussen and Sørensen, 2008). Meanwhile, the effect of fluctuations, mid-air collisions, and electrification on windblown sand movement have also been considered (e.g., Anderson, 1987; Sørensen and McEwan, 1996; Zheng et al., 2003; Dong et al., 2005; Shao, 2005; Huang et al., 2007; Kok and Renno, 2008; Kok and Lacks, 2009). The PDF distribution of the liftoff velocity is a bridge connecting studies of the microcosm and macrocosm. Although some attempts have been made to develop physical models of the grain/bed collision (e.g., Willetts and Rice, 1986; Anderson and Haff, 1988, 1991; Werner and Haff, 1988; McEwan et al., 1992; Rioual et al., 2000) and obtain the PDF distributions of possible liftoff angles and speeds, such as Gamma distribution, exponential distribution, log-normal distribution and Weibull distribution, it is generally acknowledged that the splash function remains 'poorly defined' (McEwan and Willetts, 1991), and that the specification of grain liftoff velocity is a key area of uncertainty. Nevertheless, it has been established from previous experiments (e.g.,

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Mitha et al., 1986; Nalpanis et al., 1993; Rioual et al., 2000; Beladjine et al., 2007) and numerical simulations (e.g., Anderson and Haff, 1988, 1991; Werner, and Haff, 1988; Andreotti, 2004; Kok and Renno, 2009) that the average rebound velocity is a fraction of the impact velocity, and the number of reptating grains rather than the reptating velocity increase as the impact speed increases.

Generally speaking, the intensity of the windblown sand movement is commonly quantified using the streamwise mass transport, which is the vertical integration of the streamwise mass flux. Chepil (1945) first suggested that the streamwise mass flux in the steady state decays exponentially with height above the surface, and this opinion has been verified by some experimental measurements and numerical simulations (e.g., Anderson and Hallet, 1986; McEwan and Willetts, 1991; Kok and Lacks, 2009). However, another pattern, the stratification pattern, has emerged from experimental measurements (Greeley et al., 1982; Yin, 1989; Dong et al., 2004) and numerical simulations (Anderson and Hallet, 1986; Zheng et al., 2004; Shao, 2005). The stratification pattern was discussed in detail by Zheng et al. (2004), who suggested that the streamwise mass flux is composed of a linear increment layer, a saturation layer, and a monotonic decrement layer, and the height of the peak value of the streamwise mass flux increases with the wind speed. The difference between the stratification pattern and exponential pattern lies in that the region where the linear increment layer appears is very close to the sand surface, and thus it is difficult to measure the streamwise mass flux precisely in experiments. Whether the stratification pattern appears is determined by the PDF distribution pattern of the liftoff velocity, according to the model of Shao (2005), in which the stratification pattern exists in the case of Gaussian distribution rather than exponential distribution. But in the model of Zheng et al. (2004) the stratification appears in both Gamma and exponential distributions.

In this paper the model given by Zheng et al. (2004) is employed with the PDF distribution of the liftoff velocity given by Anderson and Hallet (1986) to examine the stratification pattern. Then, based on some deterministic laws of the grain/bed collision and the Constitution Theory, a PDF distribution of the liftoff velocity is obtained and a model is established to show whether the stratification pattern exists or not, and the characteristics of the streamwise mass flux are also expounded.

2. Revaluating the previous model

There is a difference between Shao (2005), Anderson and Hallet (1986) and Zheng et al. (2004), that is the stratification in the steady state appears with the exponential distribution of liftoff velocity in Zheng et al. (2004) but not in Shao (2005) and Anderson and Hallet (1986). Hence, we use the model advised by Zheng et al. (2004) to re-examine this problem under the condition of the Gamma distribution and exponential distribution given by Anderson and Hallet (1986). The distribution functions are:

$$f(\dot{y}_0)=\frac{1}{0.63u_*}\exp\left(-\frac{\dot{y}_0}{0.63u_*}\right) \tag{1}$$

$$f(\dot{y}_0)=\frac{27}{2}\frac{1}{0.96u_*}\left(\frac{\dot{y}_0}{0.96u_*}\right)^3\exp\left(-3\frac{\dot{y}_0}{0.96u_*}\right) \tag{2}$$

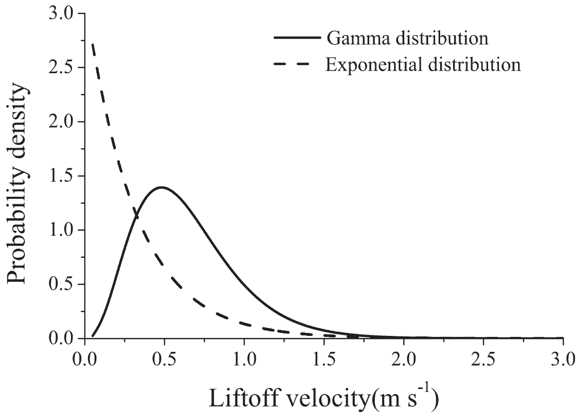

Fig. 1. Probability distribution of liftoff velocity. Friction velocity is 0.5 m s^{-1}.

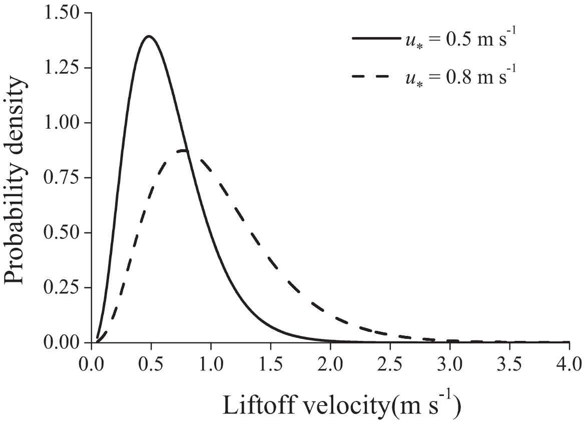

Fig. 2. Gamma distribution at the different friction velocities.

It can be found that there is considerable difference in the upper two probability distributions of liftoff velocity (Fig. 1), and the liftoff velocity of grains varies with the friction velocity (Fig. 2) in Gamma distribution. The calculation model and the parameters can be found in Zheng et al. (2004), and the minimal liftoff velocity of the grains selected in the model can hop a grain diameter due to gravity.

It is apparent in Fig. 3 that the stratification model exists with a Gamma distribution but not with an exponential distribution. The PDF distribution of liftoff velocity plays an important role in the streamwise mass flux. This finding is consistent with that of Anderson and Hallet (1986) and Shao (2005), but not that of Zheng et al. (2004), who suggested that the stratification happens with both Gamma and exponential distributions.

Zheng et al. (2004) also suggested that the height of the peak value of the streamwise mass flux increases with wind speed, and the same result can be found (Fig. 4). It can be found that the velocity has a Gamma distribution (Fig. 2), which corresponds with the peak value of the PDF distribution of liftoff velocity of 0.48 m s^{-1} as $u_*=0.5$ m s^{-1} and 0.77 m s^{-1} as $u_*=0.8$ m s^{-1}, and the hop height is, respectively, 0.00582 m and 0.01716 m in the steady state. It

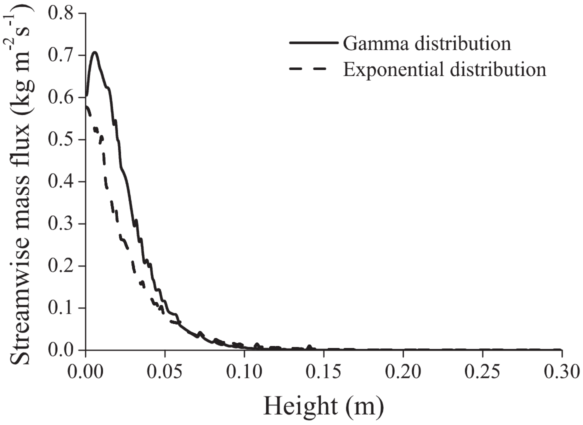

Fig. 3. The streamwise mass flux with the Gamma and exponential distribution. The friction velocity is 0.5 m s^{-1} and the diameter is 0.25 mm.