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Windblown sand saltation: A statistical approach to fluid threshold shear velocity

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ABSTRACT

The reliable prediction in probabilistic terms of the consequences of aeolian events related to sand transport phenomena is a key element for human activities in arid regions. Threshold shear velocity generating sand lifting is a key component of such a prediction. It suffers from the effect of uncertainties of different origin, such as those related to the physical phenomena, measurement procedures, and modelling. Semi empirical models are often fitted to a small amount of data, while recent probabilistic models needs the probability distribution of several random variables. Triggered by this motivation, this paper proposes a purely statistical approach to fluid threshold shear velocity for sand saltation, treated as a single comprehensive random variable. A data set is derived from previously published studies. Estimates of conditional probability distributions of threshold shear velocity for given grain diameters are given. The obtained statistical moments are critically compared to some deterministic semi empirical models refitted to the same collected data. The proposed statistical approach allows to obtain high order statistics useful for practical purposes.

1. Introduction

Aeolian sand transport is a complex process that is induced by the interaction between subfields such as wind, air suspended particles and bed-particles. It contributes to soil erosion and landform evolution. Understanding and modelling its features is of fundamental interest in many research fields. Beside the importance of windblown sand and dust in Earth sciences (Kok et al., 2012), from the engineering perspective, simulating windblown sand phenomena is relevant because of the interaction with a number of human activities and related infrastructures in arid environments (e.g. Middleton and Sternberg, 2013; Rizvi, 1989; Alghamdi and Al-Kahtani, 2005; Zhang et al., 2007; Cheng and Xue, 2014). In the infrastructure design perspective and within a probabilistic approach to design, the engineer is interested in relating a sand erosion or transport condition to a given, preferably low enough, probability of exceedance, i.e. in defining a high percentile sand transport rate.

Among the transport mechanisms responsible of sand transport, saltation largely prevails in terms of sand mass. The evaluation of the involved sand flux is usually given in terms of sand transport rate by several laws, revised for example in Dong et al. (2003), Kok et al. (2012) and Sherman and Li (2012). Most of such laws require the definition and evaluation of an erosion threshold, i.e. the minimum value of the wind shear stress at which saltation occurs. Usually, such a threshold is given in terms of threshold values of the shear velocity and depends on a number of parameters belonging to both the wind and the sand. Since the seminal work of Bagnold (1941), two threshold shear velocities have been recognized: the fluid or static threshold, defined as the minimum wind speed for initiation of sediment transport without antecedent transport, and the dynamic or impact threshold, i.e. the minimum wind speed for sustaining sediment transport with the presence of transport. Most studies proposing transport laws in steady saturated flow refer to the impact threshold (Kok et al., 2012). Hence fundamental studies (e.g. Andreotti, 2004; Pahtz et al., 2012; Kok, 2010) recently proposed models of the impact threshold in light of a few number of experimental measures, e.g. Bagnold (1937), Chepil (1945), Tsoar et al. (1994) and Li et al. (2014).

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However, the impact threshold shear velocity is approximated for application purposes as equal about %80 of the fluid threshold one (e.g.Bagnold, 1937; Pye and Tsoar, 2009; Zheng, 2009; Kok et al., 2012). Reference to the fluid threshold shear velocity is motivated by the long-standing and wide literature reviewed by Shao (2008), Pye and Tsoar (2009), Merrison (2012) and Kok et al. (2012) and summarized in the following. In the rest of the paper, we address to the fluid threshold shear velocity as "threshold shear velocity" u_{*t} for the sake of compactness.

Systematic *experimental measurements* of u_{*t} versus the grain diameter were carried out by Bagnold (1937), Chepil (1945), Zingg (1953), Fletcher (1976) and Iversen et al. (1976) amongst others. These measurements constitute the consolidated literature data base. They are reported in Fig. 1 versus the equivalent particle diameter d_{eq} (Chepil, 1951; Kok et al., 2012). A significant scatter among data can be observed notably at low values of the particle diameter. However, two general trends can be observed, divided by a local minimum at about 75–100 μm (Kok et al., 2012).

A number of *deterministic models* of the threshold shear velocity have been proposed in literature so far. They can be categorized in two classes with respect to both modelling scale and goal. *Microscopic models* discuss the equilibrium of the moments of the forces acting on the single particle resting on a bed of other particles (Shao, 2008). They aim at pointing out the physical phenomena underlying each force and at modelling it. In a general framework, entraining aerodynamic forces (drag and lift ones) induce saltation, while stabilizing forces (gravitational and the interparticle ones) counteract them (Greeley and Iversen, 1985; Shao and Lu, 2000). On one hand, the effective gravitational force including buoyancy, and the drag force correspond to well known phenomena and their modelling is widely accepted, see e.g. Greeley and Iversen (1985) and the cited reviews. On the other hand, the same does not hold for the other forces: the resultant lift force results form the Saffman one (Saffman, 1965) and the lift induced by vortical structures; the overall interparticle force results from several kinds of forces, including van der Waals forces, water adsorption forces and electrostatic forces. Although interparticle forces are expected to scale with the soil particle size (e.g. Shao and Lu, 2000), their modelling for aspherical and rough sand and dust remains poorly understood (Kok et al., 2012). In particular, such forces depend upon a number of parameters such as surface cleanliness, surface roughness at micro/nano meter scale, air and grain humidity, mineralogy and surface contaminants affecting hydrophilicity (Merrison, 2012). Semi-empirical *macroscopic models* aim at approximating the threshold shear velocity trend versus the particle diameter. Some of them are compared to the experimental data in Fig. 1(a). Because of the above modelling difficulties, they do not analytically include the contribution of lift and interparticle forces while they explicitly retain the gravitational and drag ones. Any other contribution is accounted for in a semi empirical approach by introducing one or more free parameter(s), and the value of the latter obtained by fitting experimental data. The pioneering model by Bagnold (1941) involves a single dimensionless constant A_B, resulting independent from the grain diameter or, in other terms, from Reynolds number. Then, it gives rise to a monotonic increasing trend of $u_{*t}(d)$. The model by Iversen and White (1982) defines the same parameter $A(\mathrm{Re}_{*t})$ as a piece-wise empirical function of the friction Reynolds number Re_{*t} to mimic the effects of lift and interparticle forces: the resulting $u_{*t}(d)$ law is no longer monotonic and qualitatively reflect the trend of the experimental data. The model by Shao and Lu (2000) is more compact than the previous one. It neglects the Re_{*t} dependency, and at the same time generalizes the Bagnold one by introducing a novel correction term to account for the interparticle forces. A second dimensional constant free parameter γ [N/m] is included in the correction term. More recently, McKenna (2003) has considered the effect of soil moisture on the interparticle cohesive force by defining $\gamma(\Delta P, d)$ as a function of the capillary-suction pressure deficit and of the grain diameter. Other laws of u_{*t} have been proposed for natural surfaces: they account for the effects of soil texture, soil moisture, salt concentration, surface crust, vegetation and/or pebbles on the surface. The review of such models is out of the scopes of the present paper. Interested readers can refer to Shao (2008) and Webb and Strong (2011).

Although the deterministic approach largely prevails in aeolian literature, the view that the threshold velocity should be regarded as a statistical phenomenon may be dated back to the pioneering studies by Chepil (1945). The *probabilistic modelling approach* is motivated by the scatter of the experimental data at low values of d even for a common nominal setup condition (Fig. 1-a), and by the difficulties experienced by the deterministic approach, i.e. the challenge of parameterizing threshold variability and relating this variability to its different sources.

The randomness of *bed grain geometry* and of the *turbulent wind flow* have been early recognized as sources of threshold variability in the experimental studies of Nickling (1988) and Williams et al. (1990, **?**), respectively. In particular, the wind tunnel tests by Nickling (1988) first showed that measured fluid and impact thresholds could not be reproduced, presumably because it is impossible to replicate grain positioning between each test. In fact, most sediment is composed of a range of grain sizes and shapes. Thus, for a given surface, variability is expected due to the

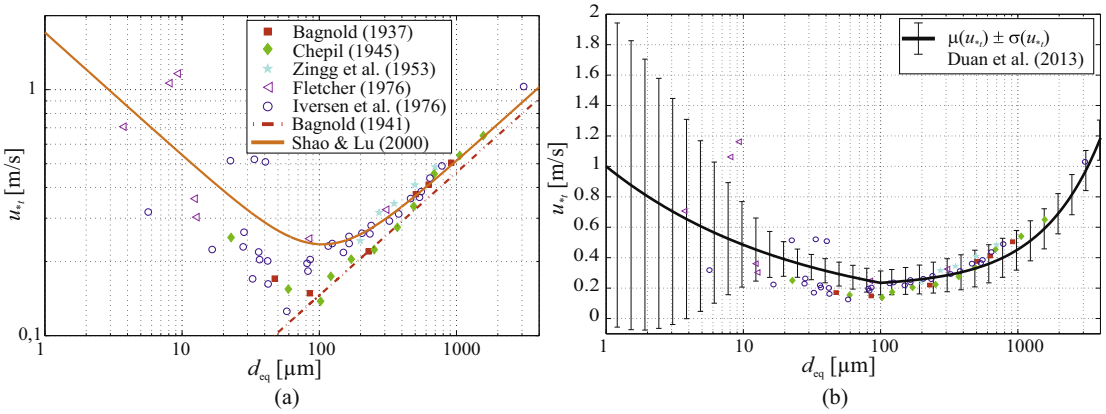

Fig. 1. Threshold friction velocity: experimental data (symbols) compared with semi-empirical deterministic models (a, redrawn after Kok et al., 2012), and the probabilistic model by Duan et al. (2013) (b).