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# Wind tunnel and computational study of the stoss slope effect on the aeolian erosion of transverse sand dunes

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ABSTRACT

To understand aeolian particle entrainment, it is important to take into account the surface slope, as most natural sand surfaces are not horizontal. The influence of slope angle on local friction velocity is the subject of this research. Three transverse triangular piles, with stoss slopes of 10°, 20°, and 32°, were tested experimentally, and modeled computationally. The wind tunnel experiments include two sets of tests: the first one consists of friction velocity measurements across the windward slope and the second set comprises the measurement of the sand dune longitudinal profile over time. The experimental tests were conducted at four undisturbed wind speeds ranging from 8.3 to 10.7 m/s.

The computational modeling was performed using a commercial CFD code, and it aimed to replicate the experimental conditions with the objective of evaluating its ability to predict the friction velocity across the windward slope. The numerical predictions of the friction velocity, for the initial longitudinal profile, show good agreement when compared to the experimental values. The region where the predicted friction velocity exceeds the threshold coincides quite well with the eroded area. The correlation between the vertical sand flux, across the stoss slope, calculated using the first eroded longitudinal profile, against the predicted friction velocity showed a cubic relation. The computational model, in view of the predicted results, seems to be a reliable tool for the estimation of the friction velocity for situations similar to those studied in this work.

## 1. Introduction

Aeolian transport of particles may have significant negative environmental impacts affecting, among others, agricultural land, pollination, air quality and built environments. Past studies on the dispersion of pollutants demonstrated the importance of dust release either from transportation or storage yards on air quality (e.g., Ferreira and Oliveira, 2009; Ferreira and Vaz, 2004). Moreover, in many parts of the world, aeolian processes have played an important role in landscape changes through accumulation or migration of sand yielding the formation of dunes, sand sheets and tongues (Pye and Tsoar, 2009; Huang et al., 2008).

The key variable in the understanding of aeolian processes and soil erosion, according several authors, such as Iversen and Rasmussen (1994), is the threshold friction velocity ($u_{*t}$), which is defined as the minimum shear velocity required for the aerodynamic forces to overcome the opposing ones. Considerable research has been conducted on this parameter through theoretical analyses, wind-tunnel experiments and field investigations as reviewed by Huang et al. (2008). Threshold friction velocity is affected by a number of factors which have been studied by several authors. For example, surface moisture is an extremely important variable controlling the entrainment process of sands by wind because the tensile force between the water molecules and sand grains produces cohesion (Dong et al., 2002). Those capillary forces between grains are the main factor responsible for the increase of the wind erosion threshold observed when the soil moisture increases (Fécan et al., 1999). The vulnerability of the soil to wind erosion depends also on the biological soil crusts (Belnap et al., 2007), crust type (Williams et al., 1995), and vegetation characteristics, such as amount and distribution, since verdure is known to affect strongly the erosion of soil by the wind (Okin, 2008). Among others, Marticorena and Bergametti (1995) and Marticorena et al. (1997) studied the influence of the surface roughness and the aerodynamic roughness height, which is the most important parameter that controls $u_{*t}$, for loose or distributed soils. Also, the presence of non-erodible roughness elements on the surface intensely attenuates the erosion of soil by wind (Raupach et al., 1993). Additional parameters, such as soil texture, distribution of grain size, or soil salt content, should be taken into account when studying the entrainment of particles by the wind in specific cases.

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Great advances have been made in understanding the physics of sand transport since the pioneering work of Bagnold (1941), who derived the following equation for a flat (subscript "0") bed:

$$u_{*t0} = A \times \sqrt{\frac{\rho_s - \rho}{\rho} gd} \tag{1}$$

In Eq. (1) $u_{*t0}$ (m/s) is the threshold friction velocity on a level surface, $\rho_s$ and $\rho$ (kg/m$^3$) are the densities of the granular material and the air, respectively, $d$ (m) is the solid grain diameter, $g$ (m/s$^2$) is the gravitational acceleration and $A$ is a general coefficient, which is nearly constant, with an assigned value of 0.1, if the fluid is air (Bagnold, 1941). When resting particles are exposed to an airstream they stay subjected to several forces, such as the aerodynamic drag, the aerodynamic lift, gravity force, and interparticle cohesive force. Eq. (1) was derived solely from the balance between drag and gravity forces, and thus describes only the behavior of $u_{*t}$ for particles with a diameter greater than 100 μm. Greeley and Iversen (1985) also considered the lift and cohesive forces and obtained a relation applicable to any range of diameters; however, this relation is rather involved mathematically. The study carried out by Shao and Lu (2000) derived a simpler expression for $u_{*t}$ through an explicit treatment of the cohesive force. Recently Barchyn and Hugenholtz (2011), instead of using analytical models (e.g., Eq. (1)), compared four methods to calculate the velocity threshold using field data.

By definition, the friction velocity is related to the wall shear stress ($\tau_w$), as follows:

$$u_* = \sqrt{\frac{\tau_w}{\rho}} \tag{2}$$

For non-horizontal situations, the study of particle entrainment processes must consider the surface slope, which may turn to be the deciding factor; it should be noted that in nature, usually sand surfaces are not horizontal. The implications of the slope on the shear stress, which is required to initiate the movement of a particular sand grain, are discussed by several researchers (e.g., Tsoar et al., 1996; White and Tsoar, 1998; Iversen and Rasmussen, 1999); for a grain laying on an upslope surface, this shear stress is larger than that for a horizontal or down sloping surface, because gravity acts contrary to the movement of the particle.

A theoretical analysis of the slope effect on threshold friction velocity was conducted by Howard (1977); based on this analysis, which was verified by Iversen and Rasmussen (1994) and Huang et al. (2008), the threshold friction velocity for the initiation of the movement of a particle resting on a tilted surface, with a slope angle $\theta$, when parameters of no primordial importance, such as the interparticle cohesive force and the Reynolds number variations, are neglected, is given by:

$$u_{*t\theta} = \sqrt{u_{*t0}^2 \left(\cos\theta + \frac{\sin\theta}{\tan\alpha}\right)} \tag{3}$$

In this equation the angle $\theta$ is the slope, while $\alpha$ is the static friction angle (or angle of repose), for which a value of 32° is commonly employed (Iversen and Rasmussen, 1994; Ferreira and Lambert, 2011).

As an alternative, instead of using the friction velocity concept, the threshold condition can be expressed through the undisturbed threshold wind velocity ($U_{0t}$), which is the minimum wind speed outside of the boundary layer necessary to drag a particle. As shown by Bagnold (1941), $U_{0t}$, for a horizontal bed, can be calculated using the following relation:

$$U_{0t} = 5.75 \times u_{*t0} \times \ln\left(\frac{z}{k}\right) \tag{4}$$

where $u_{*t0}$ (m/s), is the threshold friction velocity, given by Eq. (1), $z$ (m) is the height above the surface (in fact $z = \delta$, as beyond it $U_{0t}$ is assumed constant), and $k$ (m) is the surface roughness parameter. Similarly to the case of a slope surface, the threshold wind velocity is computed as:

$$U_{0t\theta} = 5.75 \times u_{*t\theta} \times \ln\left(\frac{z}{k}\right) \tag{5}$$

The main objective of this work is to evaluate the influence of the slope parameter on the friction velocity value, for which both experimental and numerical tests were conducted. Three models are studied, and the basic geometry consists of a two-dimensional transverse dune, with the windward slope equal to 10°, 20° and 32°, respectively. The crest height ($H$) is equal to 75 mm for all the models, and the leeward slope is equal to the angle of repose, which is taken as 32° in the present work.

Two sets of wind tunnel experiments are reported. The first one comprises the measurement of the friction velocity distribution across the stoss slope of rigid triangular models, for several undisturbed wind speeds. In the second set of experiments, the longitudinal profile of a sand dune, initially with the above mentioned triangular shape, is measured at several erosion time intervals.

The three triangular dune shapes are simulated and for their computational modeling is used the commercial *CFX* code (Ansys, 2009). The predicted friction velocity and erosion contours are compared against the experimental values.

## 2. Experimental setup

In this section of the paper it is presented the instrumentation used, the geometry of the piles studied, the sand granulometry and the procedure for the various experiments performed.

### *2.1. Wind tunnel*

The wind tunnel used for this study is installed at the Industrial Aerodynamics Laboratory (LAI) of ADAI (Association for the Development of the Industrial Aerodynamics-University of Coimbra, Portugal). The tunnel has a 2 m × 2 m cross-section nozzle followed by an open working chamber, which is 5 m long. Such short test section precludes the use of mixing devices or roughness elements to thicken or modify the boundary layer profile. The models of the piles studied were placed on the floor of the test section, and equidistant to its sidewalls. The crest of all models was positioned 2.5 m downstream of the nozzle exit, and perpendicular to the main flow direction (Fig. 1).

The profile of the mean streamwise velocity ($u$), measured in the empty working chamber, at a distance of 2.4 m from the exit of the wind tunnel nozzle, at half-width of the wind tunnel working chamber, can be described by the following power law relation:

$$\frac{u}{U_0}\left(\frac{z}{\delta}\right)^{\alpha} \tag{6}$$

where $u$ (m/s) is the longitudinal velocity component, $U_0$ (m/s) is the undisturbed wind speed, and $z$ (m) the vertical distance above the ground. Under the described conditions, the boundary layer thickness is $\delta = 0.1$ m and the profile is characterized by $\alpha = 0.11$. The turbulence intensity of the longitudinal velocity component remains nearly unchanged with the height, and a reasonable approximation is to take its value equal to 10%.

Different undisturbed velocities ($U_0$) were used for the tests, namely 8.3, 9.1, 9.9 and 10.7 m/s, which yielded four different velocity profiles as shown in Fig. 2.

When performing experiments for model-scale conditions, due attention is required to the similarity criteria, namely the equality of various dimensionless parameters, which normally is not en-