Aerodynamic and impact thresholds for cohesive mixture of sand and non-volatile liquid

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\textbf{Abstract.} The moisture has been recognized to have a significant influence on the initiation movement of sand by wind and consequently on sand transport rates. The pertinent literature regarding these phenomena is sparse and current available theoretical and empirical models exhibit considerable disagreement regarding the magnitude of moisture effects. We believe that these discrepancies come from the fact that the moisture levels are not well controlled neither properly measured and are susceptible to strongly vary over time due to evaporation. To get rid of the variability of moisture content due to evaporation, we propose a new approach based on the use of non-volatile liquid, namely silicon oil instead of water. This insures a proper control of the liquid content and the production of reliable data concerning the variation of the transport threshold with liquid content.

\section{1 Introduction}

Aerodynamic and impact thresholds are a key ingredient for aeolian sand transport description. The dependence of these thresholds with soil moisture is still poorly understood and there is a need for well-controlled experiments to improve our understanding.

For a dry sand soil, transport is initiated when the friction speed overpasses a critical value $u_{\text{td}}$ which depends on the grain diameter $D$ and particle density $\rho_p$ \cite{1}:

$$u_{\text{td}} = A \left[ \frac{(\rho_p - \rho_a)}{\rho_a} g D \right]^{0.5} \tag{1}$$

Where $A$ is an empirical coefficient \cite{2}. Typical value of the aerodynamic threshold for dry sand is $u_{\text{td}} = 0.21 \, m.s^{-1}$ for sand grains with mean diameter $D = 0.2 \, mm$ \cite{3}. There exists another threshold corresponding to the cessation transport, the so-called impact threshold $u_{\text{imp}}$. The latter is smaller than the aerodynamic threshold ($u_{\text{imp}} \approx 0.85 u_{\text{td}}$ \cite{4}) and is at the origin of hysteresis effect.

Numerous studies have been devoted to the quantification of the effect of moisture content on the aerodynamic threshold but available empirical models exhibit considerable disagreement with the magnitude of the moisture effect. For example, Belly \cite{5} who studied this effect through wind-tunnel experiments proposed the following empirical relation:

$$u_{\text{tw}} = u_{\text{td}} (1.8 + 0.6 \log_{10}(w)) , \tag{2}$$

where $w$ is the gravimetric water content, while Hotta \cite{6} provided an other empirical relation model with a linear increase of the threshold friction speed with the water content:

$$u_{\text{tw}} = u_{\text{td}} + 7.5 \, w \, I_w \tag{3}$$

where $I_w$ is a correction factor taken account for the evaporation ($I_w = 1$ if there is no evaporation).

Theoretical models were also developed. From a force balance between the grain weight $P_g$, the cohesive force $F_c$ and the wind shear stress, McKenna-Neuman and Nickling \cite{7} derived the following equation:

$$u_{\text{tw}} = u_{\text{td}} \left[ 1 + \alpha \, B_o^{-1} \right]^{0.5} \tag{4}$$

where $B_o = P_g/F_c$ is the dimensionless Bond number and $\alpha$ is a constant geometrical parameter given by

$$\alpha = \left[ \frac{2 \sin 2\beta \cos \beta}{\sin \beta} \right] \tag{5}$$

$\beta$ is the particle friction angle ($\beta \approx 30^\circ$ for a loose packing). To take benefit of Eq. 4, the knowledge of the cohesive force $F_c$ and its dependence with the water content is required, which is a challenge as well. Based on physical model considering capillary cohesive force, Kawata and Tsuchiya \cite{8} derived a relation between $F_c$ and the water content $w$ suggesting that $F_c \propto \gamma \sqrt{w}$ (where $\gamma$ is the surface tension). As suggested by Hotta, we believed that the great diversity in the experimental data regarding the effect of the moisture on the aerodynamic threshold comes from the fact of the moisture levels are not well controlled and vary in course of time due to evaporation. Recent experiments \cite{9} confirmed that for low moisture levels the transport is intermittent and is controlled by the evaporation process. Here, to get rid of the complexity of the evaporation phenomenon, we choose to work with cohesive sand.
where the water is replaced by silicon oil, a non-volatile liquid for atmospheric conditions. This allows us to conduct well-controlled experiments in a wind-tunnel and to quantify how the aerodynamic threshold but also the impact threshold vary with the liquid content.

2 Experimental setup

We carried out experiments in a wind-tunnel which has a 6.6 m working length and a 0.245 m × 0.27 m cross-section (see Fig 1). We used as a cohesive sand bed a mixture of 200 μm sand and silicone oil with a surface tension γ = 20.6 mN.m⁻¹. The portion of the wind-tunnel filled of this sand mixture is reduced to a square surface area of dimensions 0.15 m × 0.15 m with a depth of 0.02 m, either a mass of sand of M = 720 g. The sand bed is contained in a box placed 5.4 m downstream the entrance of the wind-tunnel and its surface is at the same level as the wind-tunnel floor so that there is no discontinuity. The sand bed is weighed continuously during the experiment thanks to a high accuracy scale with a working length of a 0 × 5 ϕ. 

3 Experimental Results

3.1 Erosion rate near the aerodynamic transport threshold

We first investigate the effect of the liquid content on the erosion rate to determine how the aerodynamic threshold varies with the liquid content. Fig. 3 presents the erosion rate as a function of the friction speed for various liquid content. We choose to plot the erosion rate in a semi-logarithmic plot because of the wide range of magnitude of the erosion rate. This representation underlines that the erosion rate follows a nice exponential evolution of E with the friction speed. We define the transport threshold when the mass loss during the 10 mn experiment is of the order
of the weight scale accuracy ($\Delta M < 5.10^{-2} \, g$). Doing this, we obtain the values for the aerodynamic threshold as a function of the liquid content $w$ (see Fig. 4). The aerodynamic threshold exhibits a linear increase with $w$:

$$u_{\text{std}} = u_{\text{std}} (1 + 6.15 \, w) \, .$$

This result is similar to that obtained by Hotta [6] with moist sand but differs significantly from that the logarithmic behavior found by Belly [5].

Important remarks follow. The threshold value obtained for dry sand is surprisingly high as compared with those from the literature for similar grain diameter: $u_{\text{std}} = 0.3 \, m.s^{-1}$ against $u_{\text{std}} = 0.21 \, m.s^{-1}$ (see [3]). We believe that this high value comes from finite size effect. The sand bed is so short (i.e., $15 \, cm$) and this requires the transport to be triggered on short distances. It thus turns out that the threshold is probably dependent from the length of the sand bed. It can be interesting to express our results in terms of the cohesion force (or inverse Bond number) if one takes benefit Eq. 4. We plot in Fig. 5 the dimensionless cohesive force as a function of the liquid content $w$. As expected, we obtain an increase of the cohesion force with the liquid content. We can compare the values found with the one computed from the capillary force: $F_c = \pi D \gamma \cos \theta \approx 6.5 \times 10^{-6} \, N$ (where $\theta \approx 0$ is the contact angle) which corresponds to a dimensionless force $B_{c}^{-1} \approx 130$. The magnitude of the cohesion force found from erosion threshold is thus much smaller than that given by the capillary force. This probably mean that cohesion regime we investigate falls in the hygroscopic regime and not in the pendular one where capillary bridges are formed.

### 3.2 Erosion by impact

We also investigate erosion induced the impact of saltating particles. To do this, we installed a hopper filled with dry sand on the roof of the wind-tunnel close to the entrance. This allows us to prescribe a flow of saltating particle with a mass flux $Q_{\text{in}}$. We set the mass flux value to a small value $Q_{\text{in}} = 1.4 \, g.s^{-1}$. With this incoming mass flux, the lowest friction speed we can investigate is $0 \, m/s$. Below this value, a significant fraction of the incoming sand come to rest before the sample.

We measure the erosion rate as a function of the friction speed for two different liquid content, $w = 0$ and 0.1% respectively. The incoming mass flow rate is $Q_{\text{in}} = 0.5 \, g.s^{-1}$. Open symbols correspond to data obtained for the aerodynamic erosion rate.
This means that impact is very efficient to erode a cohesive bed in comparison with the aerodynamic entrainment. Recent numerical simulations on the impact process with a cohesive bed [9] indicate that the critical inverse Bond number above which cohesion alters the impact process is of the order of $B^{-1}_o \approx 5$. As shown in Fig. 5, the range of cohesion force is always below this critical value.

4 Discussion and conclusion

The modeling of aeolian transport of wet sand requires a good description of the erosion mechanisms in presence of cohesive capillary forces. The strength of these forces are dependent on the water content within the particle bed and it is therefore crucial to have a good control of the latter to get reliable data from wind-tunnel experiments. It is however a real challenge because as soon as a turbulent air flow runs over a wet sand bed, the water content decreases rapidly and non uniformly along and within the bed due to evaporation process. To circumvent this experimental difficulty, we used a non-volatile liquid to investigate the effects of cohesion on the aerodynamic or impact threshold. This ensures that the liquid content does not vary during an experiment. Our results first indicate that the aerodynamic threshold increases linearly with the liquid content as suggested by Hotta et al. [6]. Second, we do see any measurable effect of the cohesion on the impact threshold for the range of liquid content investigated so far. This last outcome thus indicates that erosion induced by impact is hardly affected by the bed cohesion. This finding may have strong implications in the context of aeolian transport of moist sand. We expect in particular that sand transport on wet sand, once initiated aerodynamically, can be sustained at very low wind strength and leads to substantial mass transport even below the aerodynamic threshold. This may explain the surprising high transport rates observed on sand beaches despite the large level of moisture [10].

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