Aeolian sand transport with collisional suspension

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Aeolian transport is an important mechanism for the transport of sand on Earth and on Mars. Dust and sand storms are common occurrences on Mars and windblown sand is responsible for many of the observed surface features, such as dune fields. A better understanding of Aeolian transport could also lead to improvements in pneumatic conveying of materials to be mined for life support on the surface of the Moon and Mars.

The usual view of aeolian sand transport is that for mild winds, saltation is the dominant mechanism, with particles in the bed being dislodged by the impact of other saltating particles, but without in-flight collisions. As the wind becomes stronger, turbulent suspension keeps the particles in the air, allowing much longer trajectories, with the corresponding increase in transport rate. We show here that an important regime exists between these two extremes: for strong winds, but before turbulent suspension becomes dominant, there is a regime in which in-flight collisions dominate over turbulence as a suspension mechanism, yielding transport rates much higher than those for saltation. The theory presented is based on granular kinetic theory, and includes both turbulent suspension and particle-particle collisions. The wind strengths for which the calculated transport rates are relevant are beyond the published strengths of current wind tunnel experiments, so these theoretical results are an invitation to do experiments in the strong-wind regime.

In order to make a connection between the regime of saltation and the regime of collisional suspension, it is necessary to better understand the interaction between the bed and the particles that collide with it. This interaction depends on the agitation of the particles of the bed. In mild winds, collisions with the bed are relatively infrequent and the local disturbance associated with a collision can relax before the next nearby collision. However, as the wind speed increases, collision become more frequent and the agitation need not decay completely. In the regime of collisional suspension, the particles near the surface of the bed are assumed to be in a state of constant agitation. We indicate the conditions at the bed corresponding to the limits of saltation and collisional suspension and outline experiments, simulations, and modeling that have been undertaken to bridge these limits.

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Aeolian transport is an important mechanism for the transport of sand on Earth and on Mars. Understanding the natural process can also yield insight on improving the pneumatic conveying of materials to be mined for life support on the Moon and Mars. For mild winds, a few particles are in the air, but as the wind becomes stronger, the concentration of particles aloft increases, until in-flight particle collisions start to play a role. Along with this, particle-bed collisions become more frequent, and the bed behavior may change drastically, from an essentially quiescent bed to a dense agitated system. We present here a combination of experiments, simulations, and modeling that has been undertaken to understand the transition from weak to very strong winds. In particular, a collisional model that includes turbulent suspension shows that particle-particle collisions may dominate over turbulence as a suspension mechanism. Results from collisionless saltation simulations are also used to obtain an upper bound for the relaxation time of the bed.

I. INTRODUCTION

Dust and sand storms are common occurrences on Mars, and windblown sand is responsible for many of the observed surface features, such as dune fields. A better understanding of aeolian transport could also lead to improvements in pneumatic conveying of materials to be mined for life support on the surface of the Moon and Mars. Understanding the dominant mechanisms for long-term transport can also lead to understanding ancient wind regimes [1].

Figure 1 shows the different scales involved in aeolian sand transport: from dune fields that affect local winds to the few centimeters above the bed where most of the transport takes place. This study deals with the processes in the latter part. This separation of the global and local processes is possible due to the difference in scales between dune evolution times (months to centuries) and local saturation times (seconds). A dune evolution model must then combine the knowledge at all levels to predict the evolution of the surface topography [2, 3].

The usual view of aeolian sand transport is that for mild winds, saltation is the dominant mechanism, with particles in the bed being dislodged by the impact of other saltating particles, but without in-flight collisions. As the wind becomes stronger, turbulent suspension keeps the particles in the air, allowing much longer trajectories, with the corresponding increase in transport rate. We show here that between these two extremes we may have another important suspension mechanism: particle-particle collisions. This mechanism yields transport rates much higher than those predicted for saltation. The theory presented is based on granular kinetic theory, and includes both turbulent suspension and particle-particle collisions.

In order to make a connection between the regime of saltation and the regime of collisional suspension, it is necessary to better understand the interaction between the bed and the particles that collide with it. This interaction depends on the agitation of the particles of the bed. In mild winds, collisions with the bed are relatively infrequent and the local disturbance associated with a collision can relax before the next nearby collision. How-

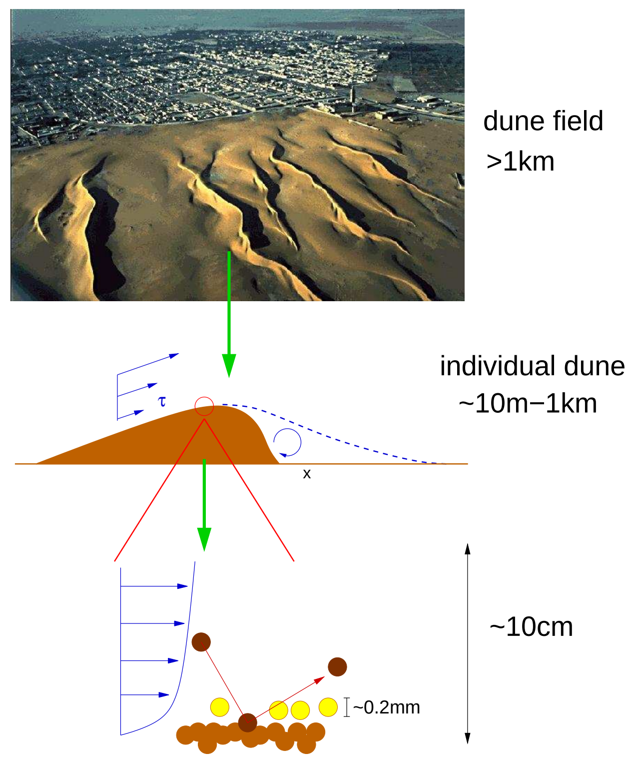

FIG. 1: Scales involved in the evolution of dunes. Upper photograph: Landsat picture of dunes encroaching on Nouakchott, the capital of Mauritania.

ever, as the wind speed increases, collisions become more frequent and the agitation need not decay completely. In the regime of collisional suspension, the particles near the surface of the bed are assumed to be in a state of constant agitation. The wind strengths for which the calculated transport rates are relevant are at the limit of current current wind tunnel experiments, and the difference between the theory and the experiments is used to provide bounds for the relaxation time of the bed. Thus these results are an invitation to do experiments in the strong-wind regime.

In order to fix notation, the grain diameter is d, gravity is g, and the Shields parameter is θ. The Shields parameter is a dimensionless measure of the free-stream stress: it is the free stream stress normalized by the buoyant weight per unit area of a solid layer of particle material one diameter in thickness.

II. BED IMPACT PROCESSES: SPLASH

For weak winds the particle-bed impacts are infrequent enough that the local agitation introduced by a previous impact has had enough time to decay. In this regime the bed impact process is described by the *splash function*, introduced by Ungar and Haff [4]. Given an impacting particle speed, the splash function gives the expected number of ejected particles and their distribution function. It also gives the distribution for the rebound of the impacting particle. In terms of dilute kinetic theory, the splash function is a complicated wall kernel with memory for the Boltzmann equation (see e.g. [5]).

Experiments on the impact of one grain on different beds were performed in Rennes. First, for two-dimensional granular packings [6], where ordering is an important issue. More recently, impacts on a 3–D disordered bed have been studied [7]. The rebound statistics agree well with those used by Werner [8]. These ongoing experiments are yielding important information on the velocity distribution of the ejecta, and also the ejection time-delay distribution. For $d = 6$ mm particles, the most probable delay is about 0.02 s, or

$$t_{\text{delay}} \approx 0.8\sqrt{\frac{d}{g}}.$$

We use this as an order-of-magnitude estimate of the relaxation time of the bed.

III. WEAK WINDS: SALTATION COMPUTATION

For weak winds, the particles in the saltation cloud are few, and they do not collide with each other. We present here computations based on collisionless saltation, following Werner [8]. We solve for the velocity distribution $f(\boldsymbol{v}; y)$ of the grains. The splash function of Ref. [8] is

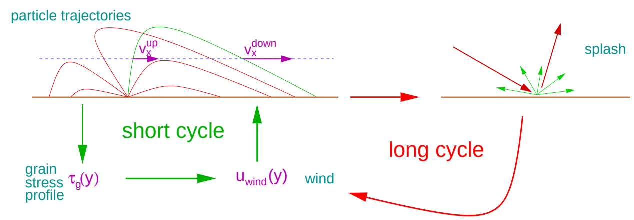

FIG. 2: Integration scheme for the saltation computation.

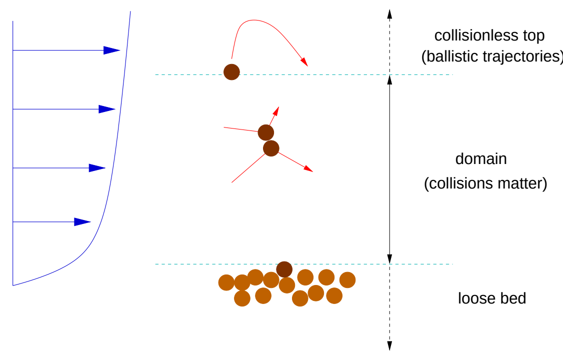

FIG. 3: Division of the domain into collisional and boundary conditions.

a boundary condition for this problem, and the integration method is the following iterative scheme sketched in Fig. 2.

IV. STRONG WINDS: COLLISIONAL MODEL

For strong winds, the number of particles in the air increases, and the particles are driven into collisions with each other. In this study the whole process is divided into three subdomains, as shown in Fig. 3. The middle section is the collisional part, where the model equations are solved. The top and bottom sections are solved in an approximate analytical fashion to yield boundary conditions (for details, see Ref. [9]).

For the middle section the unknown fields are the particle concentration profile $c(y)$, the wind velocity $U(y)$, the particle velocity $u(y)$, the particle stress $s(y)$, the granular temperature $T(y)$, the particle energy flux $q(y)$, and the collisional layer thickness h. *Note that the thickness of the collisional region is obtained as part of the solution.* Since the flow is steady and fully developed, the total shear stress is constant across the system, and it is partitioned into grain- and wind-borne stress. The equations for the particle phase are closed using granular kinetic theory, and the particles interact with the wind through viscous drag. Turbulent fluctuations in the gas are also included in a very simple way, so that the two suspension mechanisms (particle pressure gradient and turbulent suspension) can compete.

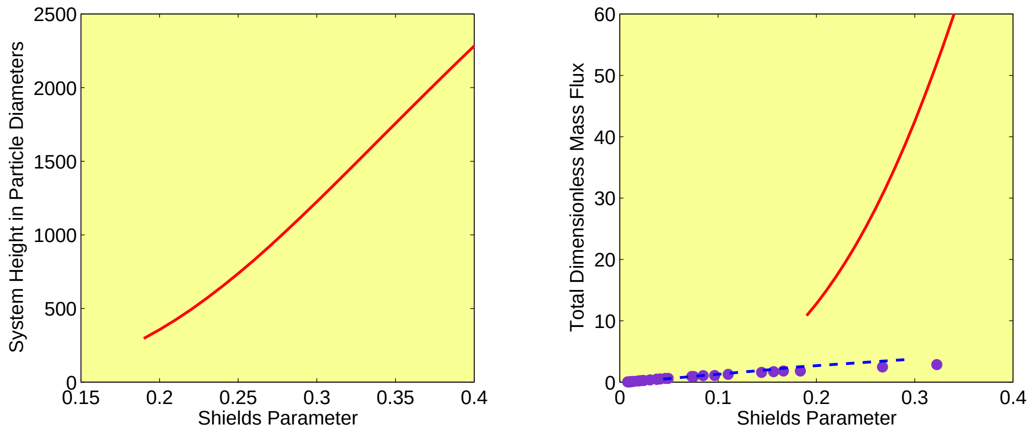

FIG. 4: Height of the collisional layer and dimensionless transport rate for 170 μm grains. Collisional model (solid line), saltation computation (dashed line), and wind tunnel experiments (circles, from Fig. 4b in Ref. [11], courtesy of K. Rasmussen).

Boundary conditions

At the bed we assume that the wind is so strong that it remains agitated bed [10]. This gives boundary conditions for the concentration (random loose packing), the wind and particle velocities (no slip for both), and the flux of particle fluctuation energy.

The particle concentration decreases strongly with increasing distance to the bed. Thus far enough from the bed we assume that the system becomes so rarefied that collisions between particles are neglected, and the trajectories are dominated by drag and gravity. This defines a characteristic particle pressure at the top of the collisional layer. The collisionless layer on top is solved analytically in an approximate way and this, together with the characteristic value of the pressure, gives boundary conditions for the particle stress and the flux of particle fluctuation energy.

V. RESULTS

Figure 4 shows the thickness of the collisional layer and the corresponding transport rate for the collisional model, for particles with $d = 170$ μm. It also shows the transport rate obtained from the collisionless saltation computation, and wind tunnel experiments from Ref. [11]. The collisionless saltation results correspond well to the wind tunnel results. The collisional model, on the other hand, overpredicts the transport rate. This mismatch is used to estimate an upper bound for the relaxation time of the bed.

The collisional model also gives enough particles aloft so that the gradient of particle pressure dominates over turbulent suspension throughout the domain.

Relaxation time for the bed

The validity of the collisional model depends on the validity of its boundary conditions. However, the splash process is a complicated dynamic behavior of a disordered granular packing. In particular the validity of the bottom boundary condition depends on how fast the bed relaxes. In other words, *the relaxation time of the bed will define how strong the wind needs to be to have an agitated bed.*

The mismatch between the experimental results and the collisional model is most likely due to the bottom boundary condition: we are assuming that the collisions with the bed are so frequent that it does not have time to return to a quiescent state. The results imply that in the wind tunnel experiments the wind is still not strong enough to break down the vailidy of the splash function concept. Preliminary simulational results of 3–D splash on disordered beds by L. Oger show that the impact of a fast particle on the bed produces ejecta at an average distance of approximately three particle diameters from the impact site (L. Oger, private communication). We use this estimate, together with the results from the collisionless computation, to obtain the average time interval between collisions of fast particles (those that will produce ejecta) on an area of the bed surface. This yields an upper bound for the bed relaxation time. Using the saltation results for $d = 170$ μm and $\theta = 0.29$:

$$t_{\text{bed relaxation}} < 2\sqrt{\frac{d}{g}}.$$

As experiments at higher Shields parameters become available, more stringent bounds can be imposed on this important parameter.

VI. CONCLUSIONS AND OUTLOOK

A combination of approaches to understand the transition from weak to strong winds were undertaken. In particular, we presented a model that includes both collisions between particles and turbulent suspension. The profiles obtained in this model show that particle-particle collisions can dominate over turbulence as a suspension mechanism.

The transport rates predicted with the collisional model are much larger than those yielded by a standard collisionless simulation and by wind tunnel experiments. This indicates that the splash function concept is still valid up to the wind speeds probed. This mismatch is used to obtain an upper bound for the relaxation time of the bed. On the other hand, the 3–D splash experiments provide the time delay between the impact and ejection of particles. This delay provides a rough lower bound for the relaxation time.

These results, together with the estimate found in Ref. [12], indicate that in-flight collisions may become important while the splash function concept is still valid. This gives two avenues for extending the models presented here:

- For the collisionless saltation computation, in-flight collisions may be included in a perturbational manner. This development is under way. Together with these calculations, further understanding of the relaxation time at the bed is required for defining the validity ranges of each approach. Molecular dynamics simulations of 3–D beds, such as those being performed by L. Oger, are especially useful to isolate the relevant processes involved.
- For the collisional model, the agitated boundary condition at the bed [10] may be replaced by a different one that allows for jumps in particle speed, concentration, and granular temperature. To perform this extension without introducing free unknown parameters, the development of these boundary conditions must be bounded by experiment.

To complement these research lines, the 3–D splash experiments are being extended to obtain more extensive information on the rebound and ejection properties of the bed.

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[1] K. D. Adams, Sedimentology **50**, 565 (2003).
[2] G. Sauermann, K. Kroy, and H. J. Herrmann, Phys. Rev. E **64**, 031305 (2001).
[3] A. R. Lima, G. Sauermann, H. J. Herrmann, and K. Kroy, Physica A **310**, 487 (2002).
[4] J. E. Ungar and P. K. Haff, Sedimentology **34**, 289 (1987).
[5] C. Cercignani, *Mathematical Methods in Kinetic Theory* (Plenum Press, New York, 1990), 2nd ed.
[6] F. Rioual, A. Valance, and D. Bideau, Europhys. Lett. **61**, 194 (2003).
[7] D. Beladjine, Rapport de Stage de DEA, Groupe Matière Condensée et Matériaux, Université Rennes1, Campus de Beaulieu Bâtiment 11A CS 74205, 263 av. du géneral Leclerc, 35042 Rennes Cedex (2003).
[8] B. T. Werner, J. Geol. **98**, 1 (1990).
[9] J. M. Pasini and J. T. Jenkins (2004), submitted to Philos. Trans. R. Soc. Lond. A.
[10] J. T. Jenkins and E. Askari, J. Fluid Mech. **223**, 497 (1991).
[11] J. D. Iversen and K. R. Rasmussen, Sedimentology **46**, 723 (1999).
[12] M. Sørensen and I. McEwan, Sedimentology **43**, 65 (1996).